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Abstract: Glacial geomorphological mapping of southern Alberta, Canada reveals landform assemblages that are diagnostic of terrestrial-terminating ice stream margins with lobate snouts. Spatial variability in the features that comprise the landform assemblages reflects changes in palaeo-ice stream activity and snout basal thermal regimes. Such changes are potentially linked to regional climate controls at the southwest margin of the Laurentide Ice Sheet. Palaeo-ice stream tracks reveal distinct inset sequences of fan-shaped flow sets indicative of receding lobate ice stream margins. These margins are demarcated by: a) large, often glacially overridden transverse moraine ridges, commonly comprising glacitectonically thrust bedrock; and b) smaller, closely spaced recessional push moraines and hummocky moraine arcs. The former southern margins of the Central Alberta Ice Stream constructed a complex glacial geomorphology comprising minor transverse ridges (MTR types 1-3), hummocky terrain (Types 1-3), flutings and meltwater channels/spillways. MTR Type 1 ridges likely originated through glacitectonic thrusting and have been glacial overrun and moderately streamlined. MTR Type 2 sequences are recessional push moraines similar to those developing at modern active temperate glacier snouts. MTR Type 3 ridges document moraine construction by incremental stagnation, because they occur in association with hummocky terrain. The close association of hummocky terrain with push moraine assemblages, indicates that they are the products of supraglacial controlled deposition on a polythermal ice sheet margin, where the Type 3 hummocks represent former ice-walled lake plains. The ice sheet marginal thermal regime switches indicated by the spatially variable landform assemblages in southern Alberta are consistent with palaeoglaciological reconstructions proposed for other ice stream lobate margins of the southern Laurentide Ice Sheet, where alternate cold, polythermal and temperate marginal conditions sequentially gave way to more dynamic and surging activity.

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Glacial geomorphology of terrestrial-terminating fast flow lobes/ice stream margins in the southwest Laurentide Ice Sheet

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Highlights

1. Landform assemblages indicative of terrestrial-terminating palaeo-ice streams.
2. Spatial variability in landforms reflects changing palaeo-ice stream thermal regime.
3. Hummocky terrain and push moraine associations indicate polythermal snouts.
4. Receding ice margins alternated between cold, polythermal and temperate conditions.

Glacial geomorphology of terrestrial-terminating fast flow lobes/ice stream margins in the southwest Laurentide Ice Sheet

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Abstract

Glacial geomorphological mapping of southern Alberta, Canada reveals landform assemblages that are diagnostic of terrestrial-terminating ice stream margins with lobate snouts. Spatial variability in the features that comprise the landform assemblages reflects changes in palaeo-ice stream activity and snout basal thermal regimes. Such changes are potentially linked to regional climate controls at the southwest margin of the Laurentide Ice Sheet. Palaeo-ice stream tracks reveal distinct inset sequences of fan-shaped flow sets indicative of receding lobate ice stream margins. These margins are demarcated by: a) large, often glacially overridden transverse moraine ridges, commonly comprising glacitectonically thrust bedrock; and b) smaller, closely spaced recessional push moraines and hummocky moraine arcs. The former southern margins of the Central Alberta Ice Stream constructed a complex glacial geomorphology comprising minor transverse ridges (MTR types 1-3), hummocky terrain (Types 1-3), flutings and meltwater channels/spillways. MTR Type 1 ridges likely originated through glacitectonic thrusting and have been glacial overrun and moderately streamlined. MTR Type 2 sequences are recessional push moraines similar to those developing at modern active temperate glacier snouts. MTR Type 3 ridges document moraine construction by incremental stagnation, because they occur in association with hummocky terrain. The close association of hummocky terrain with push moraine assemblages, indicates that they are the products of supraglacial controlled deposition on a polythermal ice sheet margin, where the Type 3 hummocks represent former ice-walled lake plains. The ice sheet marginal thermal regime switches indicated by the spatially variable landform assemblages in southern Alberta are consistent with palaeoglaciological reconstructions proposed for other ice stream lobate margins of the southern Laurentide Ice

Sheet, where alternate cold, polythermal and temperate marginal conditions sequentially gave way to more dynamic and surging activity.

Key words: terrestrial-terminating ice stream; push moraines; hummocky terrain; glacitectonic thrusting; controlled moraine; thermal regime; Laurentide Ice Sheet; palaeoglaciology

1. Introduction and rationale

The important role of ice streams in ice sheet dynamics has resulted in them becoming increasingly more prominent as a focus of multi-disciplinary research in process glaciology and palaeoglaciology. Ongoing research questions surround the issues of maintenance and regulation of ice flow, temporal and spatial patterns of activation/deactivation, large scale changes in flow regime, and potential linkages/responses to climate. Some insights into these questions are emerging from the studies of former ice sheet beds, but the focus of such research has been largely targeted at marine-terminating ice streams. Details on the marginal activity of terrestrially-terminating ice streams has only recently emerged from the study of the former ice streams of the southern Laurentide Ice Sheet, where it is clear that ice stream margins constructed lobate assemblages of moraines during deglaciation (Patterson 1997, 1998; Jennings 2006; Evans et al. 2008, 2012; Ó Cofaigh et al. 2010).

The western plains of southern Alberta, southwest Saskatchewan and northern Montana contain a wealth of glacial landforms that has been previously widely employed in reconstructions of Laurentide Ice Sheet palaeoglaciology (Stalker 1956, 1977; Christiansen 1979; Clayton & Moran 1982; Clayton et al. 1985; Evans & Campbell 1992, 1995; Evans 2000; Evans et al. 1999, 2006, 2008, 2012; Ó Cofaigh et al. 2010), while at the same time being central to conceptual developments in glacial geomorphology (e.g. Gravenor & Kupsch 1959; Stalker 1960, 1973, 1976; Clayton & Cherry 1967; Bik 1969; Clayton & Moran 1974; Moran et al. 1980; Kehew & Lord 1986; Tsui et al. 1989; Beaty 1990; Alley 1991; Evans 1996, 2003, 2009; Eyles et al. 1999; Mollard 2000; Boone & Eyles 2001; Clayton et al. 2008). Significant debate has also been recently centred on alternative, subglacial megaflood interpretations of the landforms of the region (cf. Rains et al. 1993, 2002; Sjogren & Rains 1995; Shaw et al. 1996; Munro-Stasiuk & Shaw 1997, 2002; Munro-Stasiuk 1999; Beaney & Hicks 2000; Beaney & Shaw 2000; Beaney 2002; Shaw 2002, 2010; Clarke et al. 2005; Benn & Evans 2006; Evans et al. 2006; Evans 2010). Notwithstanding the volume of publications in support of a subglacial megaflood origin for much of the glacial geomorphology of the region, we here provide a landsystems approach to the interpretation of the glaciation legacy as it pertains to the Late Wisconsinan advance and retreat of the southwest Laurentide Ice Sheet in the context of the palaeo-ice stream activity demonstrated by Shetsen (1984), Evans et al. (1999; 2006, 2008, 2012), Evans (2000) and Ó Cofaigh et al. (2010). This approach makes the assumption at the outset that subglacially streamlined bedforms and ice-flow transverse landforms are not the product of megafloods, an assumption soundly based in the arguments presented in a number of carefully reasoned ripostes (Clarke et al. 2005; Benn & Evans 2006; Evans et al. 2006) to the megaflood hypothesis. The latter have demonstrated that the western plains contain an invaluable record of palaeo-ice stream activity pertaining to the dynamics of terrestrially-terminating systems, wherein spatial and temporal patterns of ice stream operation within an ice sheet are recorded in the regional glacial geomorphology. This forms a contrast to the vertical successions of marine sediments that record the activity of marine-terminating ice streams in offshore depo-centres such as trough-mouth fans.

The overall aim of this research is to augment recent developments of the till sedimentology and stratigraphy of the western Laurentide Ice Sheet palaeo-ice stream imprints (Evans et al. 2012) with investigations of the landform signature of these terrestrially-terminating systems in southern Alberta (Fig. 1). This in turn facilitates the evaluation and reconstruction of the marginal dynamics of terrestrial palaeo-ice streams in the wider context. Specific objectives include: 1) the use of SRTM and Landsat ETM+ imagery and aerial photographs to map the glacial geomorphology of southern Alberta, with particular focus on the impact of the palaeo-ice streams/lobes proposed by Evans et al. (2008); and 2) the identification of diagnostic landforms or landform assemblages (landsystems model) indicative of terrestrial-terminating ice stream margins and an assessment of their implications for reconstructing palaeo-ice stream dynamics.

2. Study area and previous research

The study area is located in the North America Interior Plains, specifically in the southern part of the province of Alberta in western Canada, between longitudes 110°-114°W and latitudes 49°-52°N. It is bordered by the Rocky Mountain Foothills in the west, the Tertiary gravel-topped monadnocks of the Cypress Hills in the southeast and Milk River Ridge to the south (Fig. 1; Leckie 2006)). Geologically, the southern Alberta plains lie within the Western Canadian Sedimentary Basin, on a northerly dipping anticline known as the Sweet Grass Arch (Westgate, 1968). The Interior Plains in this area are composed of Upper Cretaceous and Tertiary sediments, which consist of poorly consolidated clay, silt and sand (Stalker, 1960; Klassen, 1989; Beaty, 1990). The preglacial and interglacial landscapes were dominated by rivers flowing to the north and northeast and which repeatedly infilled and re-incised numerous pre-glacial and interglacial valleys, with sediments ranging in age from late Tertiary/Early Quaternary (Empress Group) to Wisconsinan (Stalker 1968; Evans & Campbell, 1995). The Cypress Hills and Del Bonita Highlands of the Milk River Ridge formed nunataks during Quaternary glaciations (Klassen, 1989).

The striking glacial geomorphology of Alberta was primarily formed during the Late Wisconsinan by ice lobes/streams flowing from the Keewatin sector of the Laurentide Ice Sheet, which coalesced with the Cordilleran Ice Sheet over the high plains to form a southerly flowing suture zone marked by the Foothills Erratics Train (Stalker, 1956; Jackson et al., 1997, 2011; Rains et al., 1999; Dyke et al. 2002; Jackson & Little 2004). At its maximum during the late Wisconsinan, the ice flowed through Alberta and into northern Montana (Colton et al., 1961; Westgate, 1968; Colton and Fullerton, 1986; Dyke and Prest, 1987; Fulton, 1995; Kulig, 1996; Dyke et al., 2002; Fullerton et al., 2004a, b; Davies et al., 2006). Ice sheet reconstructions suggest that deglaciation from Montana started c.14 ka BP, and had retreated to the “Lethbridge moraine” by c.12.3 ka BP, after which it receded rapidly to the north (Stalker 1977; Clayton and Moran, 1982; Dyke and Prest, 1987).

Mapping of the glacial geomorphology of southern and central Alberta (Stalker, 1960; 1977; Prest et al., 1968; Westgate, 1968; Shetsen, 1987, 1990; Fulton, 1995, Evans et al., 1999, 2006, 2008) has enabled a broad identification of ice flow patterns and ice-marginal landform assemblages. Three prominent fast flowing ice lobes appear to have operated within the region and were identified as the “east”, “central” and “west lobes” by Shetsen (1984) and Evans (2000). Recently, Evans et al. (2008) suggested that the west and central lobes be referred to as the High Plains Ice Stream (HPIS) and Central Alberta Ice Stream (CAIS) respectively due to their connection to corridors of highly streamlined terrain which are interpreted as the imprint of trunk zones of fast ice flow (Fig. 1b). The CAIS has also been referred to as the “Lethbridge lobe” by Eyles et al. (1999), who highlighted that its margins were defined by the McGregor, Lethbridge and Suffield moraine belts. These moraine belts comprise landforms of various glacigenic origins, including thrust moraines, (Westgate, 1968; Stalker, 1973, 1976; Tsui et al., 1989; Evans, 1996, 2000; Evans & Rea, 2003; Evans et al., 2008), “hummocky terrain” (cf. Gravenor & Kupsch, 1959; Stalker, 1960; 1977; Shetsen, 1984, 1987, 1990; Clark et al., 1996; Munro-Stasiuk & Shaw, 1997; Evans et al., 1999, 2006; Evans 2003; Eyles et al. 1999; Boone & Eyles 2001; Johnson & Clayton 2003; Munro-Stasiuk & Sjogren, 2006) and recessional push moraines and/or controlled moraine (Evans et al. 1999, 2006, 2008; Evans 2003; Johnson & Clayton 2003). Glacially overridden and streamlined moraines also appear in the trunk zones of the fast glacier flow tracks (Evans et al. 2008), although their origins and ages remain to be elucidated. Localized case studies of large scale moraine mapping by Evans et al. (1999, 2006, 2008) have identified a spatial variability that potentially reflects changing thermal regimes at the sheet margin in addition to surging activity during later stages of recession, similar to the trends identified by Colgan et al. (2003) in the northern USA.

During deglaciation of the region, numerous proglacial lakes developed in front of the receding lobate ice stream margins, resulting in the incision of numerous spillways (Christiansen 1979;

Evans, 2000). These spillways have been either cut through pre-existing preglacial valley fills or have created new flood tracks through the soft Cretaceous bedrock (Evans & Campbell 1995). As meltwaters decanted generally eastwards, they appear to have penetrated beneath the ice sheet margin in some places to produce subglacial meltwater channels (Sjogren & Rains 1995). This pattern of drainage was most likely enhanced by the northeasterly dip in the glacioisostatically depressed land surface beneath the receding ice sheet, although regional isobases have not been reconstructed for this region due to the lack of datable lake shorelines.

A complex stratigraphy of pre-Quaternary and Quaternary glacial and interglacial deposits exists in the study region (Stalker 1963, 1968, 1969, 1983; Stalker & Wyder 1983; Evans & Campbell 1992, 1995; Evans 2000). Of significance to this study are the extensive outcrops of glacigenic sediment relating to the last glaciation, which have been employed in palaeoglaciological reconstructions of ice streams and ice sheet marginal recession patterns by Evans (2000), Evans et al. (2006, 2008, 2012) and Ó Cofaigh et al. (2010; Fig. 1c). These studies have highlighted the marginal thickening of subglacial traction tills in association with individual ice streams/lobes, thereby verifying theoretical models of subglacial deforming layers (e.g. Boulton 1996a, b) beneath ice sheets.

The findings of the research reviewed above are assimilated in this study with new observations and data on the glacigenic landforms of the region in order to assess the regional imprint of ice stream marginal sedimentation. Local variations in the landform patterns in turn facilitate a better understanding of ice stream dynamics during the deglaciation of western Canada.

3. Methods

Glacial geomorphological mapping was undertaken by using three different aerial image sources, including the 2000 Shuttle Radar Topography Mission (SRTM), Landsat 7 Enhanced Thematic Mapper Plus (Landsat ETM+) and aerial photograph mosaics flown and compiled by the Alberta Government in the 1950s. The SRTM data have been used to create digital elevation models (DEMs) of the Alberta landscape. Several authors (e.g. Glasser & Jansson, 2005; Bolch et al., 2005; Heyman et al., 2008) have used SRTM data for mapping geomorphology, but have all used it in conjunction with another data set such as Landsat 7 ETM+ and ASTER, because its resolution is not regarded as optimum for mapping exercises. Smith et al. (2006) have suggested that spaceborne sensors such as SRTM are not sensitive enough to map detailed morphology. Similarly, Falorni et al. (2005) have commented on a link between high topography and vertical accuracy errors within SRTM data sets. This implies that SRTM imagery will provide a good regional scale picture, yet where landforms exist at scales smaller than, or approaching, pixel resolution it is likely that they will not be visible, resulting in a generalized rather than a comprehensive map of the glacial geomorphology. Nonetheless, Ó Cofaigh et al. (2010) have used solely SRTM data to map ice streams in Saskatchewan and Alberta, yielding fine resolution details of subglacial bedforms and marginal moraines.

Global Mapper™ produced a smoothed, rendered pseudo-colour image of the SRTM data that could be manipulated to accentuate features, produce 3D images and change sun illumination angles. By vertically stretching the elevation data, it is possible to more easily identify landforms within the data set, providing that the exaggeration of morphology is acknowledged. Following the procedures of Smith and Clark (2005), multiple illumination angles were also used during mapping. The Global Mapper™ interface does not provide the ability to easily map the glacial geomorphology and so these manipulations were completed in Global Mapper and then exported as a GeoTIFF. Because GeoTIFFs provide only georeferenced raster imagery with no topographic information, the DEM manipulations were processed prior to GeoTIFF creation. The images were then opened in Erdas Imagine 9.0, a GIS package that enables easy mapping of the glacial landforms. In order to map these features, vector layers were created and placed on top of the exported GeoTIFFs.

An alternative method was employed to compare, verify and supplement the SRTM mapping. This involved the use of ENVI 4.3 software to open the SRTM data in a grey scale format; nearest neighbour sampling was used to correct for missing sample points and was automatically applied to the same missing data points when opening the images in Global Mapper. The files were then exported from ENVI as Bitmap Graphic files '.img', which are simply raster files that can carry both georeferenced and topographic information. This option was not available when exporting out of Global Mapper. These images were opened in Erdas Imagine 9.0 as relief shaded DEMs. The DEMs were manipulated in exactly the same manner as above, with sun illumination changes, vertical exaggeration and 3D profiling. In similar fashion to the above method, vector files were overlaid on the DEMs to map the landforms. The results were then compared to the mapping performed from the GeoTIFFs.

Additional geomorphological mapping was conducted through interpretation of the high resolution Landsat ETM+ panchromatic band (band 8: 0.52-0.90 µm) images. A mosaic of 13 scenes provided full coverage of the field site. These were downloaded from the GeoBase website (http://www.geobase.ca/geobase/en/index.html) overseen by the Canadian Council on Geomatics (CCOG). All images were in GeoTIFF format, and were georeferenced with the North American datum of 1983 (NAD83), corresponding to the Universal Transverse Mercator (UTM) projection, UTM Zone 12 for Alberta. The images were opened in Erdas Imagine 9.0 and overlaid with the same vector layers that were used to map the DEMs. This allowed first order verification of the SRTM interpretations and the mapping of additional features.

The SRTM and Landsat ETM+ mapping is at a scale appropriate to the identification of regional scale landform patterns, including subglacial bedform flowsets and cross-cutting lineations (Clark 1999). Once identified, flowsets were mapped by drawing flowlines orientated parallel to the lineation direction. Where possible, quantitative analyses examined average lineation length, orientation, elongation ratios (ER) and average distance between lineations, in order to identify any similarities or differences between flowsets. Such quantitative analyses of subglacial bedforms have been widely demonstrated to be critical in the reconstruction of palaeo-ice streams and their dynamics (e.g. Stokes & Clark, 2003a; Roberts & Long, 2005; Stokes et al., 2006; Storrar & Stokes, 2007).

Aerial photograph mosaics were utilized for large scale investigations into the landform record of the southern Alberta ice stream margins, specifically because the remote sensing methods did not have sufficient resolution. A series of ten, 1:63,360 (1 inch to one mile) aerial photograph mosaics captured in 1951 by the Alberta Department of Land and Forests were utilized for the mapping of landforms associated with the recession of the Laurentide Ice Sheet margin, especially the CAIS of Evans et al. (2008), in southern Alberta. Landforms were mapped according to their morphometric characteristics prior to interpretation, although genetic terms were later used to identify features on the maps. Linear depositional features, both ice flow-parallel (flutings, eskers) and ice flow-transverse (major and minor ridges or moraines) were mapped as single lines representing their summit crests. In areas of “hummocky terrain” (*sensu* Benn & Evans 2010), the complexity and density of individual hummocks rendered the mapping of every mound inappropriate and hence the hummocky terrain is represented by black shading of the inter hummock depressions. This approach effectively illustrates the relative degrees of linear versus chaotic patterns.

4. Results of geomorphological mapping

4.1 Regional palaeo-ice stream geomorphology: small scale mapping case studies of the HPIS and CAIS tracks

The glacial geomorphology of southern Alberta is dominated by the imprints of two fast ice flow or palaeo-ice stream tracks, which appear as corridors of smoothed topography (the HPIS and CAIS of Evans et al., 2008) bordered by lobate marginal landforms and inter-lobate/inter-stream hummocky terrain. Also, in the eastern part of the province, the subglacial bedforms and marginal moraines of Ó Cofaigh et als. (2010) 'Ice Stream 1' (“east lobe” of Shetsen 1984 & Evans 2000) terminate on the north slopes of the Cypress Hills. Previous work on regional mapping in Alberta by Evans et al. (2008) identified the fast flow tracks and various ice-flow transverse ridges, some of which were difficult to interpret due to the low resolution of the DEMs available at the time. Here we report on the comprehensive and systematic mapping and quantification of landforms in the HPIS and CAIS tracks (Figs. 1 & 2) based on higher resolution SRTM data and further developing the mapping of Ó Cofaigh et al. (2010; Fig. 1c).

The study area contains approximately 250 km of the total length of the HPIS (see Evans et al. 2008 for details of entire ice stream track) and its width varies from around 50 km along the main trunk to 85 km across the lobate terminus. A total of 714 lineations were identified along the CAIS and HPIS and together comprise seven individual flow-sets, although large areas of the smoothed corridors that demarcate the fast flow trunks do not contain terrain sufficiently strongly fluted to enable confident flowset mapping (Fig. 3). The main landforms in the HPIS trunk include at least five (Hfs_1-5) different flow sets (Fig. 3), four of which (Hfs_2-5) record marginal splaying or lobate flow within the HPIS towards the McGregor Moraine belt. The study area contains approximately 320 km of the total length of the CAIS, over which distance its width increases from 97 km to 160 km at its lobate margin (Figs. 2 & 3). One flow set (CAfs_1) was identified along the CAIS trunk, and one (CAfs_2) in its southeast corner (Fig. 3), each flow set relating to different phases of ice stream flow.

Flow set Hfs_4 contained the largest number of lineations (260) although all flow sets tended to display strong spatial coherency, and CAfs_1 contained the largest lineation at 35km long (cf. Evans 1996). Due to the resolution of SRTM imagery no elongation ratios (ERs) could be taken, however, it is apparent that most lineations have ERs of greater than 10:1. The smallest examples were found in Hfs_1 and the largest in CAfs_1 (see Table 1 for flow set data).

Flow sets display distinct relationships with ice flow transverse ridges or hummocky terrain arcs, some of which were previously documented at low resolution by Evans et al. (2008). Extensive sequences of transverse ridges exist throughout the study area, not only in marginal settings as sharp crested features but also along the HPIS and CAIS flow corridors as smoothed or streamlined features (Figs. 2, 4-8). These ridges are loosely classified below as minor or major features according to their relative sizes.

Transverse ridges associated with the HPIS reveal a clear pattern of ice-marginal advance and recession. For example, flow sets Hfs_4 and 5 terminate in zones of hummocky terrain and/or minor transverse ridges, demarcating lobate ice marginal positions which are compatible with the flow sets that terminate on their proximal sides (cf. Evans et al. 1999, 2006, 2008). The landform assemblage TR_1 occupies approximately 100 km of the western half of the HPIS track and includes an extensive sequence of low amplitude (3-6 m high), inset and arcuate minor transverse ridges (cf. Evans et al. 1999; Evans 2003; Johnson & Clayton 2003). These minor ridges appear to be draped over, or superimposed on two major ridges (Fig. 4). The summits of the two major ridges each comprise up to five component sub-ridges 10-15 m high and are overprinted by flutings, the most prominent relating to flow set Hfs_5 (Fig. 4) which continues in a southeasterly direction to cover the area known as Blackspring Ridge (Munro-Stasiuk & Shaw 2002). A further extensive series of inset arcuate minor ridges (TR_2) lies immediately south of the southernmost major ridge and, together with the TR_1 sequence, has previously been interpreted by Evans et al. (1999) and Evans (2003) as a recessional push moraine sequence.

On the CAIS footprint, CAfs_1 terminates north of the largest major transverse ridge in the study area (TR_8; Fig 5) which displays a dual lobate front and is 70 km long and crosses most of the CAIS between the Bow and Oldman Rivers, with its eastern edge connecting to an area of hummocky terrain. The ridge is weakly asymmetric, with a steeper distal slope and its height gradually increases from west to east from 20 to 30 m. The centre of flow set CAfs_1 is connected to TR_8 via an esker complex (Evans 1996, 2000) that joins the ridge at its re-entrant or inflexion point (Figs. 2 & 5). Two sets of minor transverse ridges also occur in the area located between major ridge TR_8 and the southern end of flow set CAfs_1 (Figs. 5 & 6). Assemblage TR_6 comprises broad, shallow ridges superimposed with numerous discontinuous, narrow and sharp ridges (Fig. 6). These have previously been interpreted as glacitectonic thrust ridges by Evans and Campbell (1992) and Evans (2000) based upon field exposures displaying deformed Cretaceous bedrock overlain by till. Assemblage TR_7 includes only the narrow, sharp ridges, which appear to be continuous with those in TR_6 but occupy proglacial/spillway flood tracks previously mapped by Evans (1991, 2000) and therefore have most likely been accentuated by fluvial erosion.

Further north in the CAIS footprint, it is apparent that CAfs_1 starts immediately down flow of a streamlined major transverse ridge complex (TR_5; cf. Evans 1996; Evans et al. 2008), comprising three parallel subsets of ridges rising up to 30 m above the surrounding terrain (Fig. 8A). In detail the sequence is composed of 40 ridges, ranging from 1-4 km in length and up to 5 m high. Other transverse ridges in this area include a cluster of inset minor ridges (TR_3), 30 km long and 10 – 20 m high and with crest wavelengths of 500 - 1000 m and bordered by hummocky terrain to the east, west and south. Individual ridges within the sequence are only a few kilometres in length. To the north west of TR_3 are several large ridges set within and dominating an area of hummocky terrain (TR_4). The ridge crests are 10 km long and stand up to 20 m above the surrounding hummocks. These large transverse ridge complexes are strongly asymmetric, with steeper north-facing or proximal slopes.

In the extreme south of the study area, on the preglacial drainage divide that was located between the Cypress and Sweet Grass Hills (Westgate, 1968) and 150 m above the Pakowki Lake depression (Fig. 8D), flow set CAfs_2 is located on the down ice side of major ridge assemblage TR_10, whose summit comprises a series of prominent and closely spaced, sharp crested transverse ridges (Fig. 7) which decline in height from 20 to 5 m and wavelength from 1 km - 250 m from west to east. The flow set CAfs_2 appears to be superimposed on a small area of ridges in the centre of TR_10, but elsewhere the ridges do not appear streamlined on this imagery. Further details of the smaller transverse ridges on TR_10 and the extent of flutings are presented in the next section based upon aerial photograph mapping.

Ridge complex TR_10 is separated from TR_8, located 130 km to the north, by a wide zone of minor transverse ridges, including the “Lethbridge Moraine” of Stalker (1977), which has been developed on the northern slopes of Milk River Ridge and in the Milk River drainage basin. Immediately south of the Lethbridge Moraine lies a 45 km wide and 150 km long arc of low amplitude, minor transverse ridges (TR_9; Fig. 2b), associated with numerous ridge-parallel meltwater channels and coulees (Fig. 8E). This landform assemblage has been mapped at greater detail using aerial photographs and is reviewed in the next section as a landsystem indicative of lobate terrestrial ice stream margins.

Two further sets of minor transverse ridges (TR_11 & TR_12) are located at the south west corner of Ó Cofaigh et als. (2010) ‘Ice Stream 1’. These landforms record the incursion of the “east lobe” onto the northern slopes of the Cypress Hills and against the east side of the Suffield Moraine (Fig. 2).

Hummocky terrain covers a large proportion of the study area and defines the margins of palaeo-ice stream/lobe tracks (cf. Evans 2000; Evans et al. 2008). It occurs primarily between the smoothed fast ice flow corridors (Fig. 8B) but also along the southern margin of the CAIS (Figs. 2 & 9). The SRTM and Landsat ETM+ imagery reveals a pattern of hummocky terrain that is similar to that depicted by Prest et al. (1968), Shetsen (1987, 1990), Clark et al. (1996) and Evans (2000). Detailed mapping of the landforms that occur in the hummocky terrain belts, particularly in the McGregor Moraine (Fig. 9), has previously revealed that they comprise areas of linear to chaotic hummock chains interspersed with minor ridges, interpreted by Evans (2000, 2009) and Evans et al. (2006) as a landform imprint of glacier margins that alternated between polythermal and temperate in nature during recession. Significantly in this respect, hummocky terrain bands (Stalker's 1977 "Lethbridge Moraine") run continuously from the edge of Blackspring Ridge across the CAIS marginal area up to and around the Cypress Hills. In plan form the bands demonstrate a strong lobate pattern and run parallel to intervening belts of transverse ridges, even though they internally consist of chaotic hummocks. The SRTM data reveal that the hummocky terrain and associated minor ridges are superimposed on larger physiographic features (Fig. 9a), which are likely representative of remnant uplands in the preglacial land surface (Fig. 1c; cf. Leckie 2006). The details of the hummocky terrain and associated minor ridges are presented at larger scale in the next section through a case study of the CAIS ice-marginal landsystem.

Eskers are prominent on the small scale imagery throughout the study area as narrow winding ridges, but resolution constraints allowed the identification of only the largest features. Future research will concentrate on the mapping of eskers at a much higher resolution using aerial photography and ground survey. The largest esker identified in this study was 45 km long and situated along Hfs_4 (Fig. 10). Further south, a sequence of prominent eskers is situated along the centre of the HPIS corridor, particularly in association with Hfs_5 (Figs. 2 & 4), forming a 40 km long network running parallel to lineation direction. Another prominent network of eskers is located along the eastern edge of Lake Newell and emerges 20 km south of CAfs_1 and terminates just south of Lake Newell at the inflexion point of the dual-lobate ridge TR_8 (see above; Fig. 5; cf. Evans 1996, 2000). Additional eskers were identified along the centre and eastern half of the CAIS.

4.2 Ice stream/lobe marginal landsystem: large scale mapping case study of the CAIS

Although ice flow transverse ridges have been identified at a regional scale, as described above (Figs. 2, 4-8), landform mapping from aerial photographs in combination with the SRTM data (Fig. 11) reveals a complex glacial geomorphology at larger and more localized scales, comprising minor transverse ridges, hummocky terrain, flutings and meltwater channels/spillways. These features have been developed on a land surface characterized by Tertiary gravel-capped monadnocks (e.g. Del Bonita uplands/Milk River Ridge, Cypress Hills) and substantial depressions related to long term drainage networks (e.g. Pakowki Lake depression). Previous research has investigated the nature and origins of minor transverse ridges at the margins of the HPIS and CAIS in the McGregor Moraine belt, concluding that spatial variability in morphology (controlled moraine to push moraine) likely reflects changes in the basal thermal regime of the ice sheet margin during recession (Evans et al. 2006; Evans 2009). In order to test this hypothesis, the minor transverse ridge assemblages that demarcate the receding lobate margins of the CAIS are now analysed in detail.

Transverse ridges are aligned obliquely to former ice flow and are in places contiguous with bands of hummocky terrain, forming large arcuate bands and thereby allowing the regional lobate pattern of ice stream marginal deposition to be mapped (see above). At larger scales the transverse ridges display significant variability in form and thereby inform a higher resolution palaeoglaciology. The majority of transverse ridges are located to the south and south-east of the Lethbridge Moraine and Etzikom Coulée and the most extensive sequences lie directly south of Crow Indian Lake, Verdigris Coulee and south east of Pakowki Lake (Fig. 11), where they document the early recessional phases of the CAIS margin. Within the CAIS marginal setting three types of minor transverse ridge sets are identified and classified as MTR Types 1-3 (Figs. 12-15). Additionally, three types of hummocky terrain form are recognized and classified as Types 1-3 (Figs. 16 & 17).

MTR Type 1 have largely symmetrical cross profiles and consistent wavelengths (Fig. 12), occur only in the south east corner of the CAIS margin on the TR_10 ridge complex (Figs. 2, 7 & 11) and are large enough to be identified in the regional mapping using the SRTM data (Fig. 7). Because of its ripple-like appearance in plan form, the TR_10 ridge complex has been interpreted by Beaney and Shaw (2000) as an erosional surface scoured by subglacial megaflood waters. Our large scale mapping reveals that the complex ridge TR_10 comprises three sub-sets of component ridges (Fig. 13). Ridge Set 1A comprises large sub-parallel ridges lying up ice and perpendicular to CAfs_2, and characterised by long wavelengths and intervening hollows filled with numerous small lakes (Fig. 11 & 13). Aerial photographs also reveal that the ridges are more widely overprinted by flutings than was apparent from the SRTM image (Fig. 7). Ridge Set 1B lies parallel to Set 1A but is located adjacent to the more prominent flutings that comprise flow set CAfs_2 and appears as very subtle, discontinuous and densely spaced ridges that have some resemblance to MTR Type 2 (see below). The ridges reach up to 1 km long and are no greater than 2 m high. Ridge Set 1C is located down ice of Set 1A and just north of Set 1B (Figs. 11 & 13) and individual ridges are 1-3 km long and resemble the smaller ridges within Set 1A, with similar smooth crests and water filled depressions. They are conspicuous by their north-south orientation, which is approximately 45° offset from the CAfs_2 lineament direction.

MTR Type 2 are characterized by low relief and sharp crested ridges with largely asymmetrical cross profiles and variable wavelengths; ridges often locally overlap or overprint each other and possess crenulate or sawtooth plan forms (Fig. 12; Evans 2003). They lie primarily on the flat terrain between Pakowki Lake and the MTR Type 1 ridges (Fig. 8D), south of Milk River (Fig. 11 & 13) and are characterised by conspicuous ridge sets up to 5 m in high and with generally continuous crests (Fig. 14). The ridges located along the south east margin of Pakowki Lake extend for up to 15 km, but in general the ridges range from 1-5 km long. The ridges situated south of the Milk River (Fig. 11) are more subtle and smaller than those to the south east of

Pakowki Lake. In addition to this extensive area of MTR Type 2 ridges, isolated examples of the type occur throughout the study area.

MTR Type 3 are characterized by discontinuous, low relief and sharp crested ridges that are aligned parallel and contiguous with chains of hummocks to form continuous lines when viewed over large areas. Between the high points, strongly orientated depressions, often filled with ponds and occasionally containing isolated hummocks, accentuate the overall linearity (Figs. 12 & 15). They are the most common ridge type located to the west of Pakowki Lake, and are most extensive just south of Etzikom Coulee and Verdigris Coulee (Fig. 11). Individual ridges and associated hummocks are more subtle than MTR Type 2, with smoothed crests and heights generally no greater than 3 m. They also show clear lobate form on both the regional and large scale geomorphology maps (Fig. 2 & 11), and are located on the inclined slope of the CAIS marginal area (Fig. 8A). Like MTR Type 2, the Type 3 ridges also demonstrate subtle overlapping or overprinting (Fig. 15a).

Hummocky terrain is the most common landform within the CAIS marginal zone, and contains a wide range of hummock types (Figs. 16-18). At large scales, hummock assemblages are chaotic and demonstrate little to no linearity but when viewed at smaller scales they exhibit curvilinear or lobate patterns aligned parallel to sequences of transverse ridges (Figs. 2 & 11). North of Etzikom Coulee several long thin hummocky terrain bands run parallel to transverse ridges and meltwater channels. The largest extends for 60 km from west of 112°0'0"W, between Etzikom and Chin Coulée eastwards to the north of Pakowki Lake (Fig. 11). This hummocky terrain forms part of the “Lethbridge Moraine” which extends from Lethbridge to the north slopes of the Cypress Hills (Fig. 2; Westgate, 1968; Bik, 1969; Stalker 1977). Hummocky terrain also occurs in the south west corner of the study area, where it wraps around the Del Bonita Highlands and along the Milk River Ridge. Close inspection of these hummocky terrain bands reveals three different types of hummock (Types 1-3; Fig. 17).

Type 1 hummocks form the majority of the hummocky terrain and consist of densely spaced, low relief hummocks with little or no orientation (Figs. 16 & 18). The hummocks vary significantly in size, up to 5 m in height and generally <30 m in diameter (Fig. 17). Their morphology varies from individual circular and oval shaped hummocks to interconnected larger hummocks with less rounded tops. Type 1 and Type 2 hummocks lie randomly juxtaposed with each other and make up 99% of the hummocky terrain bands. Numerous small ponds fill the depressions between the hummocks.

Type 2 hummocks are generally randomly juxtaposed with Type 1 but also form occasional larger zones within other hummocky terrain bands (Fig. 16c). They are characterised by circular mounds with a cylindrical, often water filled, hollow at their centre (Fig. 17). This creates a ring or “doughnut” shape that is noticeably different in morphology to Type 1 hummocks. Conspicuous ridges also occur within the larger zones of Type 2 hummocks (Fig. 18a). These ridges weave through the hummocks, showing no singular orientation, and occasionally make up parts of the rims of hummocks.

Type 3 hummocks are the largest of the hummock types, being up to 20 m high and 1 km wide (Fig. 17). They have a roughly cylindrical to oval plan form and are up to twice as high as the surrounding hummocky terrain. Some have large rims and all have a flat surface. They are the least common of the three hummock types but the most conspicuous. Type 3 hummocks are best developed and primarily located in the south west corner of the study area around the Del Bonita Highlands (Fig. 18a).

Flutings near the margin of the CAIS are located predominantly along the eastern portion of the Milk River and south and south east of Pakowki Lake, but also north of Tyrrell Lake (Fig. 11). They range from 1-9 km in length with an average of 2 km. Flutings located north and south of the Milk River clearly overprint MTR Type 1 (Figs. 11 & 13) at right angles and are less than 2 m in amplitude, making them difficult to recognise on the ground (Westgate, 1968). The flutings that constitute flow set CAfs_2 are notably larger than any other lineations in the CAIS marginal zone, individuals being up to 9 km long and 6 m high and the whole flow set covering an area 30 km long and 5 km wide. As a result the areal photographs reveal at least double the amount of flutings compared to the SRTM data. This scale of resolution allows further assessment of fluting dimensions, including elongation ratios, which range from 12:1 up to 85:1 along the CAfs_2 with fluting length increasing in a down flow direction.

Four major spillways extend across the study area, including Forty Mile Coulée, Chin Coulée, Etzikom Coulée and Verdigris Coulée, and lie parallel to the transverse ridges, conforming to the lobate plan form displayed by the ice-marginal landform record (Fig. 11). They extend across the majority of the "Lethbridge Moraine" sequence as dominant features, reaching up to 500 m wide and 60 m deep (Fig. 19). An extensive network of smaller channels situated north of Chin Coulée (Fig. 11 & 19) lie predominantly parallel but also perpendicular to the spillway. These shallow channels are up to 10 km long and 200 m wide (Fig. 19). Longer channels up to 20 km long and 100 m wide are found to the north of Crow Indian Lake, dissecting the hummocky terrain band at right angles. Only a few eskers were identified and are located chiefly in the north east corner of the area mapped in Figure 11.

5. Interpretations of geomorphology mapping

5.1 Smoothed corridors, lineations and flutings

Smoothed "corridors" of terrain on the plains of western Canada have been previously interpreted as palaeo-ice stream tracks or footprints (Evans et al. 2008; Ó Cofaigh et al. 2010) based upon the geomorphological criteria proposed by Stokes and Clark (1999, 2001; Table 2). The "corridors" contain MSGL or flutings and are delineated by a change in smoothed topography, created by fast ice flow, to hummocky terrain associated with slow moving, cold based ice and stagnation (Dyke & Morris 1988, Stokes & Clark 2002, Evans et al. 2008; Evans 2009; Ó Cofaigh et al. 2010). Similarly, we here compare the lineations and smoothed topography of southern Alberta to previously identified palaeo-ice streams (Patterson 1997, 1998; Stokes and Clark, 1999, 2001; Clark and Stokes, 2003; Jennings, 2006) and to the forelands of contemporary ice streams on the Antarctic Shelf (Shipp et al., 1999; Canals et al., 2000; Wellner et al., 2001; Ó Cofaigh et al., 2002), and thereby substantiate proposals for the former occurrence of the HPIS and CAIS in the southwest Laurentide Ice Sheet. The onset zones of both the HPIS and CAIS are unknown and mapping by Prest et al. (1968) and Evans et al. (2008) do not identify any clear convergent flow patterns. However, till pebble lithology data (Shetsen 1984) demonstrate a Boothia type (Dyke & Morris 1988) dispersal by the HPIS and CAIS. Based on the reconstructed flow sets and landforms it seems clear that both the HPIS and CAIS represent ‘time-trangressive’ ice streams (Clark and Stokes, 2003).

Topographic cross profiles (Fig. 8B) and topographic maps (Geiger 1967) reveal that the CAIS is a ‘pure’ ice stream and the HPIS a predominantly ‘topographic’ Ice stream (Clark and Stokes, 2003). The HPIS traversed across the easterly sloping terrain of the High Plains (Hfs_2-5; Fig. 3), but Cordilleran and Laurentide ice coalescence during the LGM forced the HPIS to flow in a southeasterly direction, as highlighted by the different orientations of Hfs_1 and Hfs_2-5 (Fig. 3). Additionally, the 90° shift of the HPIS between Hfs_1 and 2 (Fig. 3) is positioned approximately where the Foothills Erratics train is located, which has been used to mark the location of ice sheet coalescence (Stalker, 1956; Jackson et al., 1997; Rains et al., 1999). The multiple flow-sets along the HPIS therefore document numerous small scale flow re-organisations during deglaciation controlled by lobation of the ice stream margin. Hfs_5 (Fig. 3) is composed of numerous lineations that on a small scale demonstrate strong spatial coherency. However, large scale mapping compiled by Evans et al. (2006) identifies cross cutting lineations which must have been formed during more than one flow event.

Few flow sets were identified along the CAIS track and a lack of obvious cross-cutting patterns hampers any identification of changing flow directions. However, the orientation of flow set CAfs_1 appears to relate to lobate ice flow towards the dual lobate ridge TR_8 (Figs. 3 & 5), indicating that TR_8 could represent the maximum position of a re-advance during which flow set CAfs_1 was aligned obliquely with the lobate ice margin. Transverse ridge sets TR_6 and TR_7 appear to represent later readvances by the CAIS lobe that terminated north of TR_8. This would explain the streamlining of a major esker network by CAfs_1 to the north of TR_6 and TR_7 and its preservation in a non-streamlined state to the south (Evans 1996, 2000), where it documents the development of a significant subglacial/englacial drainage pathway at the junction of two ice flow units in the CAIS; the latter is indicated by the dual lobate TR_8 ridge and the coincidence of the esker complex at the apex of the ridge re-entrant (Fig. 5; see *Section ii* below).

In the marginal zone of the CAIS in south and south east Alberta (Fig. 11), MSGL and smaller flutings overprint MTR Types 1 and 2, specifically to the south and south east of Lake Pakowki. Because the streamlining of the MTR is mostly only cosmetic, their construction and overriding was likely not related to initial advance of the ice sheet to its LGM limit but rather a localized re-advance of the ice sheet margin; potential candidates are the Altawan advance of Kulig (1996) and the Wild Horse advance of Westgate (1968). This advance impacted on the terrain between the Cypress Hills and the longitude of 112°W, approximately 15 km east of Del Bonita. The minor flutings in the area run parallel to flow set CAfs_2 and so, based on their strong parallel coherency, are interpreted to represent the same flow event. Lineation length gradually increases from northwest to southeast, trending into several MSGLs within CAfs_2 (Fig. 11). All measured ERs within the CAIS marginal area are greater than the 10:1 minimum threshold proposed by Stokes and Clark (2002) for fast flowing ice.

The locations of CAfs_1 and 2 (Fig. 3) on the down ice side of bedrock highs that appear to have been glacitectonically thrust and stacked (see *Section iii* below) and at locations where the proglacial slope dips down ice (Fig. 8A & D), suggest that topography may have been a controlling factor in their production. Similar lineation occurrences on the down ice sides of higher topography are found within Hfs_5 on Blackspring Ridge (Fig. 2; Munro-Stasiuk & Shaw 2002) and the Athabasca fluting field in central Alberta (Shaw et al., 2000), an observation also made by Westgate (1968), who further highlights the occurrence of the largest flutings in such settings. If this is a significant factor in lineation and MSGL production, it would explain why there are so few lineations along the CAIS where the regional slope predominantly dips up ice (Fig. 8A). This evidence is consistent with the groove ploughing theory for lineation production (Clark et al., 2003) whereby ice keels produced by flow over bedrock bumps carve grooves in the bed and deform sediments into intervening ridges or flutings. The surface form of the northern end of the megafluting complex at the centre of CAfs_1 is instructive in this respect in that it appears as a flat-topped ridge with grooves in its summit (Evans 1996, 2000).

5.2 Transverse ridges

A variety of large transverse ridges were initially identified on DEMs by Evans et al. (2008) who interpreted them as either overridden or readvance moraines based upon their morphology and some localized exposures, the latter indicating a glacitectonized bedrock origin. The higher resolution SRTM data used in this study facilitate a more detailed assessment of these forms.

The streamlining and lineation overprinting of the two major arcuate ridges within the TR_1 sequence (Figs. 2 & 4) document the southerly advance of the HPIS over the site after major ridge construction. The arcuate nature of the ridges indicates that they were constructed as ice marginal features and so likely record an earlier advance of the HPIS to this location. The two major ridges occur at a location where the bedrock topography rises 30-60 m above the surrounding terrain (Geiger, 1967) and are significantly different in morphology to the minor ridges that lie over, between and south of them (Fig. 2). Their size, multiple crests and location on a bedrock rise are compatible with glacitectonic origins, similar to numerous other examples in southern Alberta, where the Cretaceous bedrock is highly susceptible to disruption due to glacier advance (Bluemle & Clayton 1984; Aber et al., 1989; Aber & Ber 2007).

Similarly, in the east, ridge sets TR_3 & 4 (Fig. 2) are locally known as the Neutral Hills and have been traditionally recognized as glacitectonic thrust block moraines (Moran et al. 1980; (Aber & Ber 2007). Previous mapping in the area of TR_3 by Kjearsgaard (1976) and Shetsen (1987) identified significantly fewer transverse ridges but did propose an ice thrust origin. Ice thrusting was also proposed by Kjearsgaard (1976), Shetsen (1987) and Evans et al. (2008) for ridge set TR_4. Glacitectonic origins are also most likely for TR_5 & 6 (Fig. 2), because they occur on bedrock highs (Fig. 8A) and hence are influenced by topographical controls (Tsui et sl.

1989; Bluemle & Clayton 1984; Aber et al., 1989), comprise closely spaced, parallel and predominantly linear multiple ridge crests, and internally contain glacitectonized bedrock (Evans & Campbell 1992; Evans 1996; Evans et al. 2008). The overall arcuate plan forms of both TR_5 and TR_6 also supports an ice-marginal origin. Based on this evidence both sets of ridges are interpreted as ice thrust ridges formed by compressive ice marginal flow (cf. Evans, 1996, 2000; Evans et al., 2008). A thin till cover situated on top of the ridges suggests that they are actually cupola hills (Aber et al. 1989; Benn & Evans 2010; Evans 2000) produced by the overridding CAIS margin (Evans, 2000). Ridge set TR_7 is a locally fluvially modified part of sequence TR_6 and so it is most likely that they share similar origins.

The large dual-lobate ridge (TR_8) has previously not been identified and is hereafter named the "Vauxhall Ridge" after the nearest town. It is almost certainly ice marginal, based on its dual-lobate plan form, and lies down ice and perpendicular to CAfs_1 and the subglacially streamlined Lake Newell esker complex (Fig. 5; Evans 1996), which suggests that it records the re-advance limit of the CAIS. The ridge also continues into hummocky terrain and transverse ridges to the east, which are therefore interpreted to have formed contemporaneously. The geomorphic expression of the Vauxhall Ridge provides few indicators as to its precise genetic origins, and so further investigation of sub-surface structure is required.

Ridge sets TR_11 & 12 (Fig. 2) are interpreted as a single sequence of ridges formed at the margin of the "east lobe" or 'Ice Stream 1' of Ó Cofaigh et al. (2010). Extensive sections through the ridges show that they have been glacitectonically thrust and stacked (Ó Cofaigh et al. 2010), indicating an ice thrust origin.

Similar glacitectonic origins are proposed for some of the transverse ridges mapped at larger scales in the CAIS margin case study. Specifically, all three sub-types of the MTR Type 1 ridges of the CAIS marginal landsystem (TR_10; Fig. 2) likely originated through glacitectonic thrusting and have been overrun by a re-advancing ice margin. The largest ridges (Set A, Fig. 13) are overprinted with lineations and their tops have been smoothed by ice flow. The ridges are composed of deformed bedrock (Beaney & Shaw 2000), an observation used to support a proglacial thrusting origin by Westgate (1968), Shetsen (1987) and Evans et al. (2008). Their location along the preglacial drainage divide suggests that topography was significant in their formation; glacier flow would have been compressive (Fig. 8D) and porewater pressures in the weak Cretaceous bedrock would have been elevated, a situation highly conducive to glacitectonism (Bluemle & Clayton 1984; Aber et al. 1989; Tsui et al. 1989). Although a glacitectonic origin is the most appropriate interpretation for ridge Type 1A, MTR Types 1B and 1C display more subtle characteristics that hamper confident process-form interpretations. Type 1B ridges (Fig. 13) have been heavily modified by glacier re-advance and are barely distinguishable in the landform record. Their orientation parallel to Type 1A ridges suggests that they formed during the same advance and therefore possibly by the same mechanism, although initial relief was modest. Type 1C ridges are very similar in form to Type 1A ridges but have been significantly modified into more subtle and smoothed features. Based on their similar morphology and location on the preglacial divide they are also interpreted as overridden thrust ridges.

MTR Type 2 sequences (Fig. 12), primarily located east and south east of Pakowki Lake and south of the Milk River (Figs. 8D, E & 11), display an inset (en echelon) pattern that closely resembles that of push moraines presently developing at active temperate glaciers, for example at Breiðamerkurjökull and Fjallsjökull in Iceland (Price 1970; Sharp 1984; Boulton 1986; Matthews et al. 1995; Krüger 1996; Evans & Twigg 2002; Evans 2003; Evans & Hiemstra 2005). These modern analogues have been used by Evans et al. (1999, 2008) and Evans (2003) to support the interpretation of the whole sequence of transverse ridges within the CAIS marginal area as recessional push moraines, a more specific genetic assessment than the previous conclusions of Westgate (1968) that the landforms represented “washboard moraine”, “linear disintegration ridges” and “ridged end moraine”. A recessional push moraine origin implies that the CAIS margin must have been warm based during landform construction, reflecting seasonal climate variability (Boulton 1986; Evans & Twigg 2002; Evans 2003).

The origins of MTR Type 3 are indicated by the style of hummock (see section *iv* below) visible within the linear assemblages that make up the component ridges. The individual hummocks that predominate within MTR Type 3 vary between Type 1 and Type 2 hummocks, which are interpreted below as having formed supraglacially. This implies that significant englacial debris concentrations characterized the margin of the CAIS at the time of MTR Type 3 formation. Debris provision could have been related to either englacial thrusting and stacking of debris rich ice due to compressive flow against the reverse regional slope (Fig. 8A; Boulton, 1967, 1970; Ham & Attig, 1996; Hambrey et al., 1997, 1999; Glasser & Hambrey, 2003) or incremental stagnation (Eyles, 1979; 1983; Ham & Attig, 1996, Patterson, 1997; Jennings, 2006; Clayton et al., 2008; Bennett & Evans 2012). In the case of incremental stagnation, the moraine linearity would be related to either the high preservation potential of controlled moraine (Gravenor & Kupsch, 1959; Johnson & Clayton, 2003), an unlikely scenario based upon modern analogues of controlled moraine development (Evans, 2009; Roberts et al., 2009), or active recession of a debris charged ice margin brought about by warm polythermal conditions and accentuated by upslope advances (Evans 2009). This is supported by the fact that, although MTR Type 3 sequences are composed of contiguous linear hummock tracks and discontinuous ridges (Figs. 11, 12, 14 & 15), small scale mapping (Fig. 2) shows clear inset sequences of MTR Types 2 and 3, typical of active recession of both the CAIS and HPIS margins in southern Alberta (note that the minor ridges in TR_1 are MTR Types 2 & 3) based upon modern analogues of active temperate and warm polythermal glaciers (Boulton 1986; Evans & Twigg 2002; Colgan et al. 2003; Evans 2003, 2009; Evans & Hiemstra 2005).

5.3 Hummocky terrain

Type 1 hummocks represent the largest proportion of hummocky terrain within the CAIS marginal area. Concentrations of Type 1 hummocks occur around the Del Bonita highlands and in the lobate bands of hummocks north of Etzikom Coluée (Fig. 11), also known as the Lethbridge moraine (Stalker, 1977). Previous work in Alberta (Gravenor & Kupsch, 1959; Stalker, 1960; Bik, 1969) has identified that a significant proportion of Type 1 hummocks are composed of till. A supraglacial origin for Type 1 hummocks can be supported by simple form analogy (cf. Clayton, 1967; Boulton, 1967, 1972; Parizek, 1969; Clayton & Moran, 1974; Eyles, 1979, 1983; Paul, 1983; Clayton et al., 1985; Johnson et al., 1995; Ham & Attig, 1996; Patterson, 1997, 1998; Mollard, 2000; Johnson & Clayton, 2003; Jennings, 2006), but their juxtaposition with active recessional moraines in lobate arcs of landform assemblages (Fig. 11 & 16) suggests that they were not associated with widespread ice stagnation. Differential melting and supraglacial debris reworking by continuous topographic reversal can be invoked to explain the irregular shapes and sizes of the hummocks when viewed at larger scales, although subglacial pressing of the soft substrate at the margin of the CAIS, as proposed by Stalker (1960), Eyles et al. (1999) and Boone and Eyles (2001), could have been operating in the poorly drained conditions of the reversed proglacial slopes of the region (Klassen, 1989; Mollard 2000). Nevertheless, the lobate arcuate appearance of Type 1 hummocks when viewed at smaller scales has a strong resemblance to the controlled moraine reported by Evans (2009) and the hummock assemblages along the southern Laurentide Ice Sheet margins described by Colgan et al. (2003) and Johnson and Clayton (2003) as their "Landsystem B". The corollary is that, during early deglaciation, the edge of the CAIS was cold based and part of a polythermal ice sheet margin, beyond which there was a permafrost environment (Clayton et al. 2001; Bauder et al. 2005); several generations of ice wedge casts around the Del Bonita (Jan Bednarski, personal communication) and the Cypress Hills uplands (Westgate, 1968) verify ground ice development around the receding CAIS margin.

North of the CAIS marginal zone, Type 1 hummocks are extensive and well developed, and therefore have been the subject of numerous investigations (e.g. Stalker, 1960, Munro-Stasiuk and Shaw, 1997; Eyles et al., 1999; Boone and Eyles, 2001; Evans et al., 2006). Comparison of Figure 2 and existing maps (cf. Shetsen, 1984, 1987; Clark et al., 1996; Evans et al., 1999) shows that hummocky terrain mapping using SRTM data is capable of a high degree of replication. Due to its position between corridors of fast flowing ice lobes, the hummocks have been used to demarcate an 'interlobate' terrain by Evans et al. (2008), but the more generic term 'hummocky terrain' is preferred here. Nonetheless, the abrupt transition from smoothed topography (corridor) to hummocky terrain along the CAIS margin is interpreted as a change in subglacial regime, and hence demarcates the flow path of the ice stream (cf. Dyke & Morris 1988; Patterson 1998; Evans et al. 2008; Ó Cofaigh et al. 2010). Glacitectonic evidence identified along the north shore of Travers Reservoir, demonstrates that some linear hummocks and low amplitude ridges in hummocky terrain are in fact thrust block moraines (Evans et al., 2006) formed by ice flow from the north east, indicative of CAIS advance into the area after the HPIS had receded. The input from the HPIS is demarcated by flow sets Hfs_4 and 5 (Fig. 3) which flow into the 'McGregor moraine'. Detailed investigation of this area by Evans et al. (2006) reveals that the hummocky terrain, when viewed at large scale, comprises inset recessional push ridges and associated arcuate zones of flutings similar to modern active temperate glacial landsystems (Evans et al. 1999; Evans & Twigg, 2002; Evans 2003; Evans et al. 2006; Evans et al. 2008). The hummocky terrain therefore represents a less linear set of ice-marginal landforms to those with which it is laterally continuous in the HPIS trunk immediately to the west (Fig. 2). The reconstructed ice margins show that ice was flowing into the area from the northwest (Evans et al., 2006), and so most likely represent the termination of flow set Hfs_5.

Type 2 hummocks resemble the "doughnut hummocks" or "ring forms" that are common to many deglaciated ice sheet forelands in mid-latitude North America and Europe (e.g. Gravenor & Kupsch 1959; Parizek 1969; Aartolahti 1974; Lagerbäck 1988; Boulton & Caban 1995; Mollard 2000; Colgan et al. 2003; Knudsen et al. 2006). Johnson and Clayton (2003) demonstrate that doughnut hummocks across North America are predominantly composed of clayey till, which they suggest is important to hummock formation. Several genetic models have been proposed, all of which regard the landforms as indicative of a 'stagnant glacial regime' (Knudsen et al. 2006), but they remain poorly understood. Importantly, like Type 1 hummocks, the fact that Type 2 hummocks are often contiguous with push ridges appears to contradict the stagnation model. Because Type 2 hummocks are contiguous with not only recessional push moraines but also Type 1 and Type 3 hummocks (see below), which are supraglacial in origin, it follows that doughnut hummocks most likely also originated as supraglacial debris concentrations (controlled moraine) in a polythermal ice sheet margin. Alternative origins for

Type 2 hummocks include proglacial blow-out features created by over-pressurized groundwater (Bluemle 1993; Boulton & Caban 1995; Evans et al 1999; Evans 2003, 2009) and subglacial pressing of saturated sediments (Gravenor & Kupsch 1959; Stalker 1960; Aartolahti 1974; Eyles et al. 1999; Mollard 2000; Boone & Eyles 2001), although the latter would not produce linear chains of hummocks lying between arcuate push moraine ridges.

The conspicuous ridges that occur in association with Type 2 hummocks (Fig. 18a) and are often continuous with hummock rims must document the more extensive operation of the rim forming process. This could involve either: a) the elongation of hollows between controlled moraines during melt-out, giving rise to preferential deposition in linear chains of ice-walled channels or supraglacial trough fills (Thomas et al. 1985); and/or b) occasional ice-marginal pushing during the overall downwasting of a debris-charged snout upon which controlled moraine was developing (cf. Evans 2009; Bennett et al. 2010; Bennett & Evans 2012).

Type 3 hummocks closely resemble the ice-walled lake plains of the southern Laurentide lobes in Minnesota, North Dakota, Wisconsin, Michigan and southern New England (Colgan et al., 2003; Clayton et al., 2008) and throughout Europe (Strehl, 1998; Knudsen et al., 2006). Strong evidence presented by Clayton et al. (2008) demonstrates that ice-walled lake plains cannot be of subglacial origin based on molluscs present within the enclosed deposits. Their presence therefore is unequivocally associated with supraglacial origins, the corollary of which is that any adjacent hummocky terrain is also of supraglacial origin (Johnson & Clayton 2003; Clayton et al., 2008). The large sizes of the Type 3 hummocks can be explained by their continued development after ice recession due to a thick insulating debris cover (Attig, 1993; Clayton et al., 2001; Attig et al., 2003; Clayton et al., 2008), hence also their absence from the active recessional imprint of the CAIS marginal area. The close association between ice-walled lake plain development and permafrost (Attig, 1993; Clayton et al., 2001; Attig et al., 2003) is also evident within the CAIS marginal area, whereby the largest ice-walled lake plains are located around the Del Bonita Highlands where permafrost features have also been recorded (Bednarski, personal communication).

6. Discussion

6.1 Overview and chronology

The regional glacial geomorphology of southern Alberta primarily records the deglacial dynamics of the south west margin of the Laurentide Ice Sheet, within which three major ice streams (HPIS, CAIS of Evans et al. 2008 and “Ice Stream 1” or “east lobe” of Ó Cofaigh et al. 2010 and Shetsen 1984 respectively) coalesced and flowed against the north-easterly dipping topography, thereby damming proglacial lakes and diverting regional drainage during advance and retreat (Shetsen 1984; Evans 2000; Evans et al. 2008). In combination with the available deglacial chronology for the region (cf. Westgate 1968; Clayton & Moran 1982; Dyke & Prest 1987; Kulig 1996) the ice-marginal landforms are now used to chart ice sheet retreat patterns (Fig. 20).

Although the existing chronology is not well constrained by absolute dates, it is appropriate to acknowledge Westgate’s (1968) five distinct morphostratigraphic units (Elkwater drift; Wild Horse drift; Pakowki drift; Etzikom drift; Oldman drift), each of which has been taken to represent a re-advance limit in south east Alberta based on petrography and morphology. The Elkwater drift relates to the upper ice limit on the Cypress Hills. The Wild Horse drift extends into northern Montana where it terminates at a large 15-20 m transverse ridge sequence and is interpreted to represent the final advance of the CAIS margin into Montana sometime around 14 ka BP. The Pakokwi drift (Fig. 20) is marked by the outer extent of the push moraines to the south east of Lake Pakowki and runs along the northern tip of the Milk River and north around the Cypress Hills (Wesgate, 1968; Bik, 1969; Kulig, 1996). Therefore, all landforms to the south of this point were formed during an earlier advance, most likely the Altawan advance (15ka BP; Kulig, 1996). The Pakowki advance (Fig. 20), not recognized in Christiansen’s (1979) or Dyke and Prest’s (1987) deglacial sequences, most likely occurred between 14-13.5 ka BP (Kulig, 1996) and relates to Clayton and Moran’s (1982) Stage F - H. The Etzikom drift limit is interpreted as the "Lethbridge moraine" limit of Stalker (1977) and is marked in Figure 20 by the broad band of hummocky terrain just north of Etzikom Coulée. This ice margin maintained its position along the Lethbridge moraine until around 12.3ka BP (Stage I, Clayton and Moran, 1982; Dyke and Prest, 1987; Kulig, 1996). The Oldman drift limit (Fig. 20) is located just south of the Oldman River. Importantly, the correlation between the thrust ridges at Travers Reservoir (Evans et al., 2006) and the Oldman limit suggests that they were formed during this re-advance episode. The corollary is that the HPIS had already receded further to the north. This re-advance (Stage J – L, Clayton and Moran, 1982) most likely occurred just after 12ka BP. Based on the regional geomorphology map (Fig. 2) it is suggested that a further re-advance occurred (Vauxhall advance), the limit of which is marked by the Vauxhall Ridge and must have occurred sometime after 12ka BP. Evans (2000) suggests that the CAIS margin had receded to the north of the study area by 12ka BP. Based on the Vauxhall advance evidence, the CAIS must have receded later than that proposed by Evans (2000). Importantly, Dyke and Prest (1987) place the ice sheet margin to north of the study area by this time, and so this suggests that the CAIS may have remained within southern Alberta for longer than previously thought. The Vauxhall ridge is interpreted to mark the final re-advance of the CAIS after which time it receded rapidly (Evans, 2000). The exact timing of the HPIS and east lobe retreat are unclear, but it seems likely that the HPIS had receded somewhere north of Bow River by 12ka BP.

6.2 Landsystem model of the terrestrial terminating ice stream margin

The juxtaposition of the moraine types of southern Alberta is illustrated in Figure 21a and used in Figure 21b to construct a conceptual landsystem model for terrestrial terminating ice stream margins. This model implies that terrestrial ice stream margins are subject to changing thermal conditions and dynamics, often at small spatial and temporal scales. Various parts of the ice stream beds of western Canada have been interpreted previously as manifestations of specific landsystems based upon similarities with modern analogues; for example, Evans et al. (1999, 2008) have identified an active temperate landform signature in the HPIS imprint and a surging signal in the Lac la Biche ice stream. Additionally, switches in basal thermal regime have been invoked by Evans (2009) to explain inset suites of different moraine types associated with the recession of the HPIS margin in the McGregor Moraine belt. Thermal regime switches and intermittent surges during recession have been proposed elsewhere in reconstructions of southern Laurentide Ice Sheet palaeoglaciology. For example, Colgan et al. (2003) identify three characteristic landsystems which they interpret as the imprint of an ice lobe with changing recessional dynamics. The outermost landsystem of a drumlinized zone grading into moderate- to high-relief moraines and ice-walled lake plains represents a polythermal ice sheet margin with sliding and deforming bed processes giving way to a marginal frozen toe zone. Inboard of this landsystem lie fluted till plains and low-relief push moraines, a landsystem indicative of active temperate ice recession. This in turn gives way to a landsystem indicative of surging activity. At a regional scale, Evans et al. (1999, 2008) and Evans (2009) have promoted similar temporal and spatial variability in ice stream landform imprints in Alberta, but the large scale mapping reported here allows a finer resolution record of such changes to be elucidated for ice sheet margins during the early stages of deglaciation.

6.3 Dynamics of the Alberta terrestrial terminating ice stream lobes

The Alberta ice streams flowed over a substrate composed of Cretaceous and Tertiary sediments, consisting of poorly consolidated clay, sand and silt. The Cretaceous beds in particular are prone to glacitectonic folding and thrusting due to a high bentonite content, which is reflected by the quantity and size of thrust features within southern Alberta. Additionally, the drainage conditions caused by swelling clays will have almost certainly created elevated porewater pressures and localized impermeable substrates, giving rise in turn to fast glacier flow (Clayton et al., 1985; Fisher et al., 1985; Klassen, 1989; Clark, 1994; Evans et al., 2008). Bedrock highs, many of which are controlled by residual Tertiary gravel caps (monadnocks), will likely have created resistance to ice flow (e.g. Alley, 1993; Joughin et al., 2001; Price et al., 2002; Stokes et al., 2007) and caused localised compression, highlighted by the presence of thrust ridges at such locations. Additionally, the reverse gradient of the easterly dipping bedrock surface will have initiated significant marginal compressive flow which also would have resulted in glacitectonic disturbance and well developed controlled moraine on debris-charged snouts. The region is thereby an ancient exemplar of geologic setting exerting strong controls on the location and flow dynamics of ice streams (Anandakrishnan et al., 1998; Bell et al., 1998; Bamber et al., 2006), although it is difficult to ascertain whether fast ice motion occurred through deformation or sliding or a combination of the two. Numerous till units and up ice thickening till wedges within southern Alberta (Westgate, 1968; Evans & Campbell, 1992; Evans et al., 2008, 2012) are consistent with the theory of subglacial deformation (Alley, 1991; Boulton, 1996a, b), although Evans et al. (2008) argue that the presence of large subglacial channels and thin tills overlying thin stratified sediments and shale bedrock along the CAIS trunk indicates that deformation was subordinate to sliding.

A clear change in landform assemblages from south to north along the axis of the CAIS documents a temporal change in ice stream/lobe dynamics. Initial advance of the CAIS was responsible for the glacitectonic construction and overriding of large transverse ridges in bedrock (cupola hills). The extent of modification or streamlining of these landforms decreases in a southerly direction, as illustrated by the superficial fluting of TR_10 south of Lake Pakowki, which reflects the short duration of overriding by the CAIS. Long flutings to the south of TR_10 record fast glacier flow or ice streaming when the margin of the CAIS lay in Montana. Although the dynamics of the CAIS during Laurentide Ice Sheet advance are difficult to reconstruct, the construction of large thrust moraines are most commonly associated with surging glacier snouts and therefore this mode of flow during advance cannot be ruled out. During deglaciation the dynamics of the CAIS switched from fast flow/streaming to steady state flow towards a lobate margin with a changing sub-marginal thermal regime. This is recorded by the arcuate bands of MTR Type 1 – 3 ridges and hummocky terrain located between the preglacial divide (Milk River Ridge) and the Bow River catchment. Specifically, the sequential south to north change from hummocky terrain to MTR Type 2 to MTR Type 3 in this area records a temporal switch in ice marginal characteristics, from cold polythermal to temperate and then to warm polythermal (cf. Colgan et al. 2003; Evans 2009). A similar switch in sub-marginal thermal characteristics has been proposed for the HPIS by Benn and Evans (2006) and Evans (2009) to explain a south to north change in moraine characteristics. Based upon the chronology of ice sheet recession presented in Figure 20, it appears that the switch to temperate conditions occurred at approximately the same time in both the CAIS and HPIS, indicating a potential climatic control. A contrasting landform assemblage north of the Bow River basin documents a further change in CAIS dynamics, wherein overridden thrust moraines, megaflutings (CAfs_1) and a fluted esker complex lie inboard of the Vauxhall Ridge. This assemblage is interpreted as the imprint of a fast flow/streaming event, a precursor to the surges that constructed thrust moraines (e.g. TR_3) and crevasse-squeeze ridges to the north of the study area (Evans et al. 1999, 2008). Recession of the CAIS margin is demarcated between the surge limits by inset sequences of marginal and sub-marginal meltwater channels and spillways (Fig. 2).

7. Conclusions

Glacial geomorphological mapping from SRTM and Landsat ETM+ imagery and aerial photographs of southern Alberta has facilitated the identification of diagnostic landforms or landform assemblages (landsystems model) indicative of terrestrial-terminating ice stream margins with lobate snouts. Spatial variability in landform type appears to reflect changes in palaeo-ice stream activity and snout basal thermal regimes, which are potentially linked to regional climate controls at the southwest margin of the Laurentide Ice Sheet.

Small scale mapping case studies of the High Plains (HPIS) and Central Alberta (CAIS) palaeo-ice stream tracks reveal distinct inset sequences of fan-shaped flow sets indicative of receding lobate ice stream margins. The lobate margins are recorded also by large, often glacially overridden transverse moraine ridges, commonly constructed through the glacitectonic thrusting of bedrock, and smaller, closely spaced inset sequences of recessional push moraines and hummocky moraine arcs (minor transverse ridges). The locations of some MSGL on the down ice sides of high points on ice stream beds is consistent with a groove-ploughing origin for lineations, especially in the case of the megafluting complex at the centre of CAfs_1 which appears as a flat-topped ridge with a grooved summit. During deglaciation the dynamics of the CAIS in particular switched from fast flow/streaming to steady state flow towards a lobate margin, which was subject to changing sub-marginal thermal regimes as recorded by the arcuate bands of MTR Type 1 – 3 ridges and hummocky terrain located between the preglacial divide (Milk River Ridge) and the Bow River catchment.

Large scale mapping of the southern limits of the CAIS reveals a complex glacial geomorphology relating to ice stream marginal recession, comprising minor transverse ridges (MTR types 1-3), hummocky terrain (Types 1-3), flutings and meltwater channels/spillways. MTR Type 1 ridges likely originated through glacitectonic thrusting and have been glacial overrun and moderately streamlined. MTR Type 2 sequences are recessional push moraines similar to those developing at modern active temperate glacier snouts. MTR Type 3 ridges document moraine construction by incremental stagnation, because they occur in association with hummocky terrain. This localized close association of the various types of hummocky terrain with push moraine assemblages as well as proglacial permafrost features, indicates that they are not ice stagnation landforms but rather the products of supraglacial controlled deposition on a polythermal ice sheet margin, where the Type 3 hummocks represent former ice-walled lake plains.

The ice sheet marginal thermal regime switches indicated by the spatially variable landform assemblages in southern Alberta are consistent with palaeoglaciological reconstructions proposed for other ice stream lobate margins of the southern Laurentide Ice Sheet, where alternate cold, polythermal and temperate marginal conditions sequentially gave way to more dynamic and surging activity. The sequential south to north change from hummocky terrain to MTR Type 2 to MTR Type 3 within the Lethbridge Moraine and on the northern slopes of the Milk River ridge records a temporal switch in CAIS marginal characteristics, from cold polythermal to temperate and then to warm polythermal. This is similar to patterns previously identified for the HPIS at approximately the same time based upon the available regional morphochronology and hence indicates a potential regional climatic control on ice sheet marginal activity. To the north of the Lethbridge Moraine, the landform assemblage of the Bow and Red Deer river basins, comprising overridden thrust moraines, megaflutings (CAfs_1) and a fluted esker complex lying inboard of the Vauxhall Ridge, records a later fast flow/streaming event. This was the precursor to the later ice stream surges that constructed the large thrust moraines TR_3 and TR_4 and other surge-diagnostic landforms in central Alberta.

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Figure captions

Figure 1: Location, bedrock topography and palaeo-ice stream maps of the study area: a) location maps, showing the province of Alberta, Canada and the study area outlined by two boxes. The larger box covers the area depicted in Figure 3 and the smaller box the area depicted in Figure 2; b) bedrock topography map, from The Geological Atlas of the Western Canadian Sedimentary Basin (Alberta Energy and Utilities Board/Alberta Geological Survey, 1994), including the locations of the CAIS and HPIS ice streams of Evans et al. (2008). The map highlights the regional NNE dipping slope. The study area is outlined by two boxes with the larger box representing Figure 3 and the smaller box representing Figure 2; c) palaeo-ice stream map superimposed on the SRTM imagery of Alberta and western Saskatchewan, from Ó Cofaigh et al. (2010), with ice stream activity represented as numbered phases. The CAIS and HPIS are part of the phase 1 activity in the western half of the image; d) location map of the study area depicted in Figure 2, showing geographical features and place names.

Figure 2: Glacial geomorphology map of southern Alberta based upon the mapping of SRTM imagery undertaken in this study: a) map of landforms with genetic classifications; b) map of landforms annotated with place names and the locations of Figures 4-7 & 9-11, the transverse ridge sets and topographic cross profiles A-E (see Fig. 8).

Figure 3: Flow-sets reconstructed from glacial lineations. Lineations were grouped into flow sets based primarily on their orientation but also their proximity and location (Clark 1999). Hfs_1-5 relate to the High Plains Ice Stream and CAfs_1 & 2 relate to the Central Alberta Ice Stream.

Figure 4: SRTM data of transverse ridges situated along the HPIS trunk (TR_1). Note the streamlined features that make up Hfs_5 to the right of the image and the esker network in the bottom right corner.

Figure 5: SRTM data of large lobate ridge situated along the CAIS. The Bow River flows through the centre of the image and the Oldman River along the bottom. Also shown are TR_6, TR_7 and TR_8, and an esker network situated to the right centre of the image.

Figure 6: SRTM data of the western section of transverse ridges that cross the entire CAIS (TR_6, Fig. 2).

Figure 7: SRTM data of the sequence of ridges in the south eastern corner of Alberta (TR_10). Note the lineations situated just down ice of the ridges (CAfs_2) and the smooth flat topography in the north west corner representing Pakowki Lake.

Figure 8: Topographic profiles taken from SRTM data (see Figure 2 for location) across the study area: A) long profile of the bed of the CAIS; B) transverse profile across the beds of the HPIS and CAIS and the McGregor and Suffield moraine belts; C) transverse profile across the terrain traversed by the HPIS; D) ice flow parallel profile from Pakowki Lake across the transverse ridges located on the preglacial drainage divide in southeastern Alberta; E) transverse profile across the terrain covered by the CAIS marginal landforms.

Figure 9: Example of hummocky terrain in the McGregor Moraine: a) Landsat ETM+ image of the moraine assemblage, with McGregor Lake visible as the flat, smooth area in the left centre and the Little Bow and Bow rivers at the bottom and top of image respectively; b) larger scale aerial photograph image of the hummocky terrain to the south east of McGregor Lake, located by the box in Figure 9a.

Figure 10: Flow set Hfs_4 from SRTM data in GeoTIFF format, demonstrating the high level of spatial coherency and a large esker indicated by white arrows.

Figure 11: Glacial geomorphology map of the landforms produced at the margin of the CAIS. Black shaded areas represent lakes and ponds, and therefore demarcate the extent of meltwater channels/spillways and smaller scale depressions between hummocks and ridges. Minor transverse ridge crests are depicted as black arcuate lines and major transverse ridges by barbed lines. Flutings are represented by straight lines orientated oblique to transverse ridges. Black circular symbols represent the largest flat-topped

mounds or ice-walled lake plains. Hatched broken lines depict the margins of major channels. The typical morphological details of the hummocky terrain, represented here by densely spaced small scale depressions, are illustrated and summarized in Figures 16 and 17 respectively.

Figure 12: Morphological characteristics of transverse ridge sets within the CAIS marginal zone. Type 1 ridges are symmetrical in form and have smoothed summits separated by partially water filled depressions (the dotted line represents the crest of the ridge). Type 2 ridges have sharper crests and vary in wavelength. Type 3 ridges are composed of numerous strongly orientated hummocks and ridges separated by partially water-filled depressions with occasional hummocks.

Figure 13: Transverse ridge sets Types 1 and 2 located in the SE corner of the CAIS marginal Zone and overprinted by lineations. Individual ridge types are identified in a) and c).

Figure 14: Type 2 and 3 ridges: a) aerial photograph mosaic and b) geomorphology map of Type 2 transverse ridges, located to the east of Pakowki Lake (see Fig. 11). The northwest corner of the image and map shows Type 3 ridges blending into Type 1 hummocky terrain; c) Type 2 ridges located 5km to the north of image in a) and b) (centre of image is 49˚ 23.5' N and 110˚ 44' W); d) and e) ground views showing the parallel, smooth crested and discontinuous nature of Type 3 transverse ridges.

Figure 15: Type 3 transverse ridges located in the central portion of the CAIS marginal zone (see Fig. 11). Individual hummocks and ridge segments are arranged contiguous with each other, giving rise to linearity in the landform record: a) area located between Verdigris Coulée and the Milk River; b) area located south of Crow Indian Lake and Etzikom Coulée.

Figure 16: Examples of Type 1 and 2 hummocks: a) predominantly Type 1hummocks north of Pakowki Lake (centre of image is 49˚ 28' N & 111˚ 09' W); b) predominantly Type 1 hummocks north of Crow Indian Lake (centre of image is 49˚ 26' N & 111˚ 39' W; c) predominantly Type 2 hummocks north of Pakowki Lake (centre of image is 49˚ 28' N & 110˚ 54.5' W (see also Fig. 21a).

Figure 17: Morphological characteristics of hummocks within the "Lethbridge Moraine"

sequence. The dimensions reflect the largest features in each class.

Figure 18: Examples of hummocky terrain in an aerial photograph mosaic of the area to the east of Del Bonita, showing the juxtaposition of all 3 hummock types. Also within the image are the ridges (highlighted by the white arrows) that run through some hummocky terrain bands. Note that here they run between Type 2 hummocks and in places constitute parts of the hummock rims (centre of image is 49˚ 04.5' N & 112˚ 37'W).

Figure 19: Details of meltwater channels and spillways: a) view eastwards along Etzikom Coulée; b) aerial photograph extract of the network of channels to the north of Chin Coulée (centre of image is 49˚ 37.5' N & 111˚ 38' W; c) ground view of shallow channels in the aerial photograph.

Figure 20: Reconstructed palaeoglaciology of the southern Alberta ice streams/lobes during deglaciation based on published chronologies (Westgate 1968; Clayton & Moran 1982; Dyke & Prest 1987; Kulig 1996) and constrained by geomorphology presented in this paper: a) Pakowki advance limit around 14-13.5ka BP; b) Etzikom limit located along the Lethbridge moraine at around 12.3ka BP; c) Oldman limit at approximately 12ka BP; d) Vauxhall limit tentatively dated at around 11.7ka BP. The reconstructed position of the HPIS is based solely on geomorphology and so the chronology of the marginal positions is speculative. The proglacial lakes are minimal reconstructions based upon previous work by Westgate (1968), Shetsen (1987) and Evans (2000).

Figure 21: Ice stream marginal end moraine zonation/landsystem model: a) aerial photograph mosaic of the area to the north of Pakowki Lake, showing the gradation from Type 2 ridges in the southeast corner of the image, through Type 1 to Type 3 and then to hummocky moraine with intermittent bands of Type 3 in a northwesterly direction; b) conceptual model of the continuum of landforms created by terrestrial ice stream margins based primarily on the CAIS case study. Active recessional push moraines (Types 1 & 2 ridges) document temperate snout conditions during which the lobate ice stream margin responded to seasonal climate drivers. Fluted terrain containing well developed esker networks were active at these times. Hummocky moraine arcs containing ice-walled lake plains, kame mounds and short esker segments represent

cold-based lobe margins when controlled moraine was constructed by widespread freeze-on and stacking of basal debris rich ice sequences. Between these two ends of the landform continuum lie moraine arcs composed of aligned hummocks and ponds (Type 3 ridges), indicative of polythermal margins that probably responded to intermediate timescale (decadal) climate drivers. During later stages of recession, the margin of the CAIS underwent surging, as documented by the surging landsystem signature in areas to the north of the study area by Evans et al. (1999, 2008).

Table 1: *Data showing the specific characteristics of the flow-sets, which in turn act as a device to help differentiate between particular flow sets.*

Flow set	Number of lineations	Mean length (km)	Mean direction (˚)	Flow set area (km^2)
Hfs_1	81	1.56	224	702
Hfs_2	110	3.42	141	3162
Hfs_3	66	2.34	119	1631
Hfs_4	260	3.58	170	4150
Hfs_5	147	3.52	160	5964
CAfs_1	30	10	182	6154
CAfs_2	20	4.17	118	849

Table 2: Palaeo-ice stream criteria of the CAIS and HPIS compared to the schema proposed by Stokes and Clark (1999, 2001).

Ice Stream Geomorphological Criteria (Stokes and Clark, 1999, 2001)	CAIS	HPIS
1. Characteristic shape and Dimensions	YES	YES
2. Highly convergent flow patterns	Unknown	NO
3. Highly attenuated bedforms	YES	YES
4. Boothia type erratic dispersal train	YES	YES
5. Abrupt lateral margins	YES	NO
6. Ice stream marginal moraines	YES	YES
7. Glaciotectonic and geotechnical evidence of pervasively deformed till	YES	YES
8. Submarine till delta or sediment fan (trough-mouth fan)	NA*	NA*

* large arcuate assemblages of moraines and thick, complex sequences of tills and associated glacigenic sediments reported at the former HPIS and CAIS margins by Evans et al. (2008, 2012) are likely to be the terrestrial equivalents of trough-mouth fans.

Figure 1a
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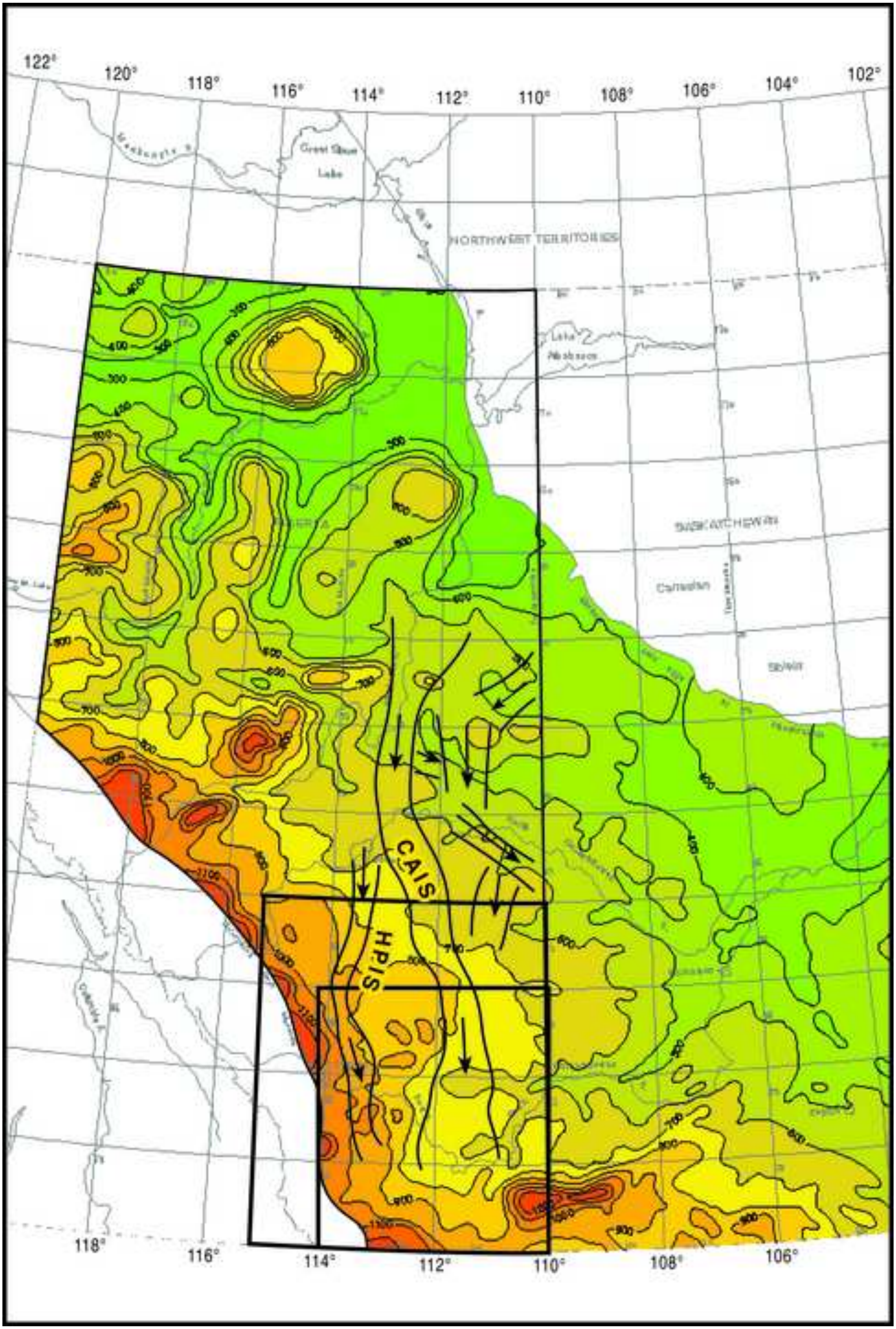

Figure 1c

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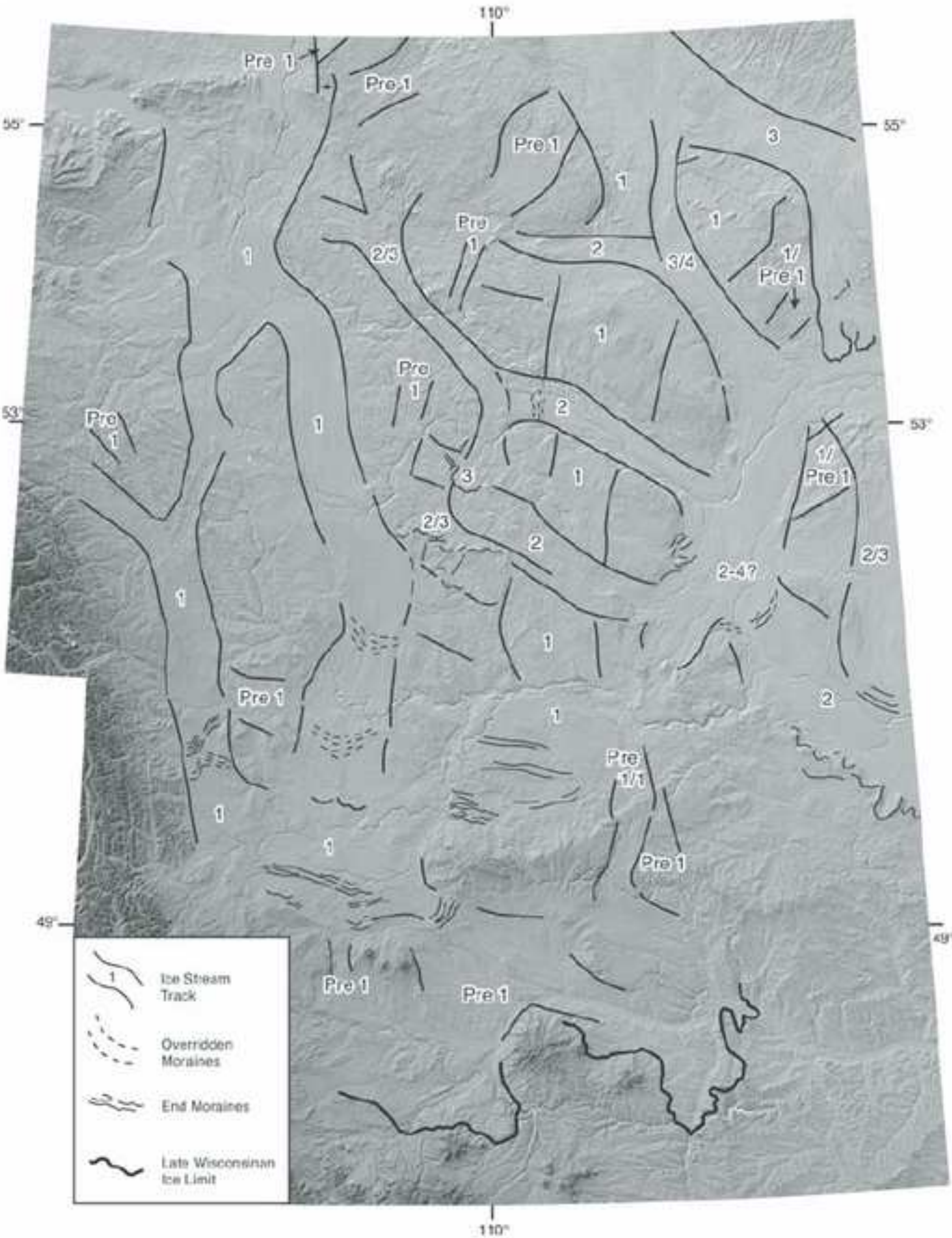

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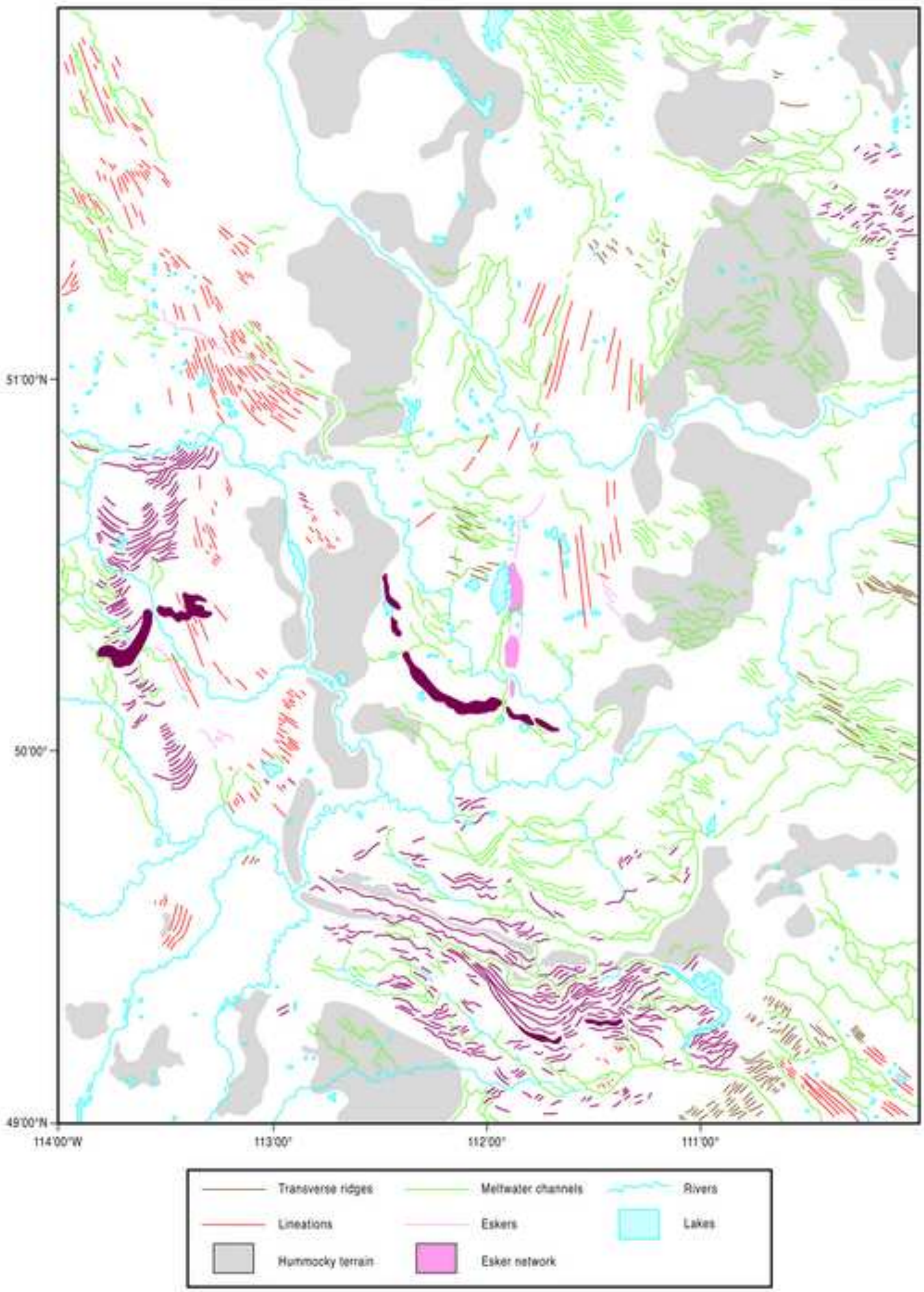

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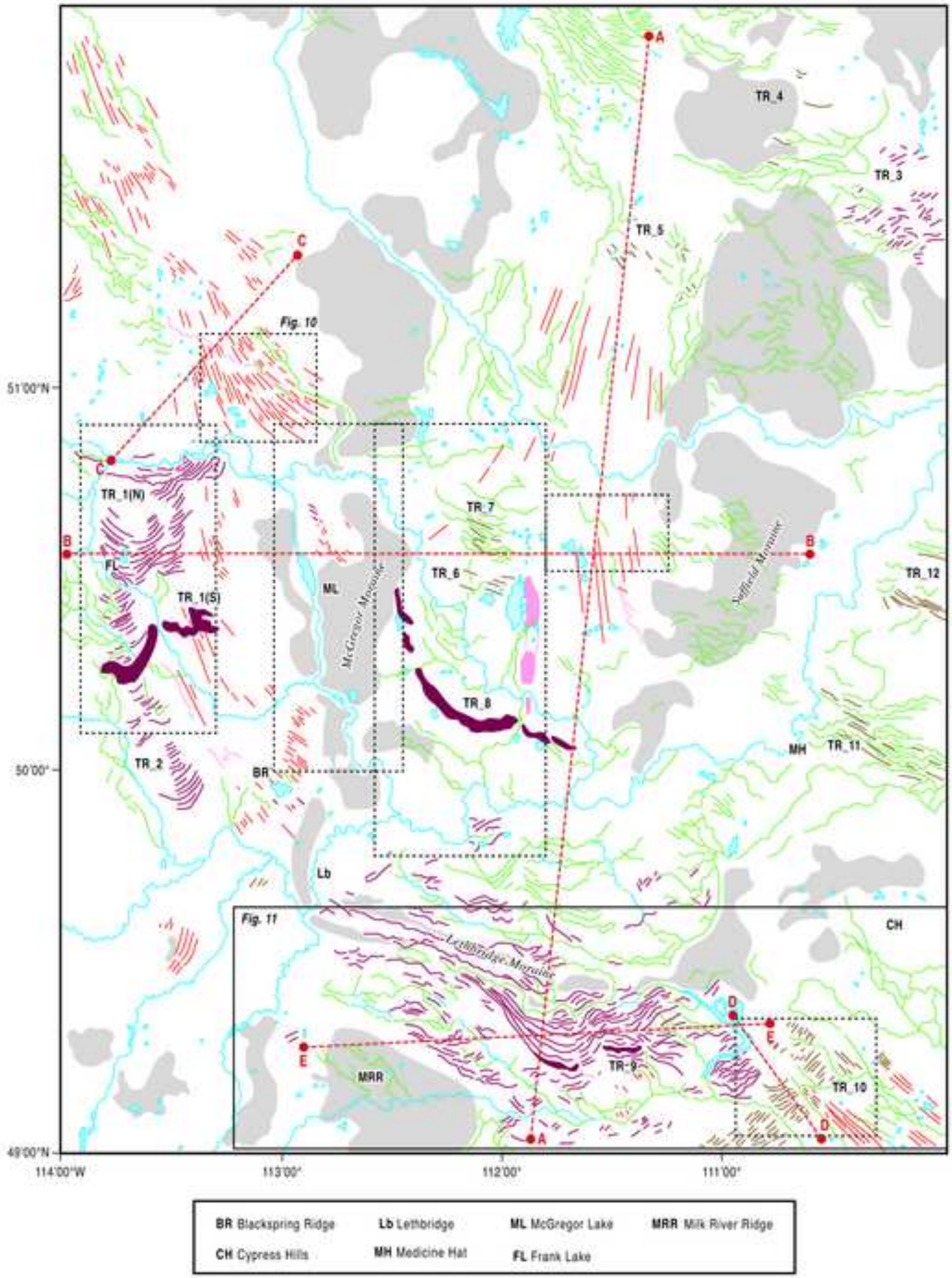

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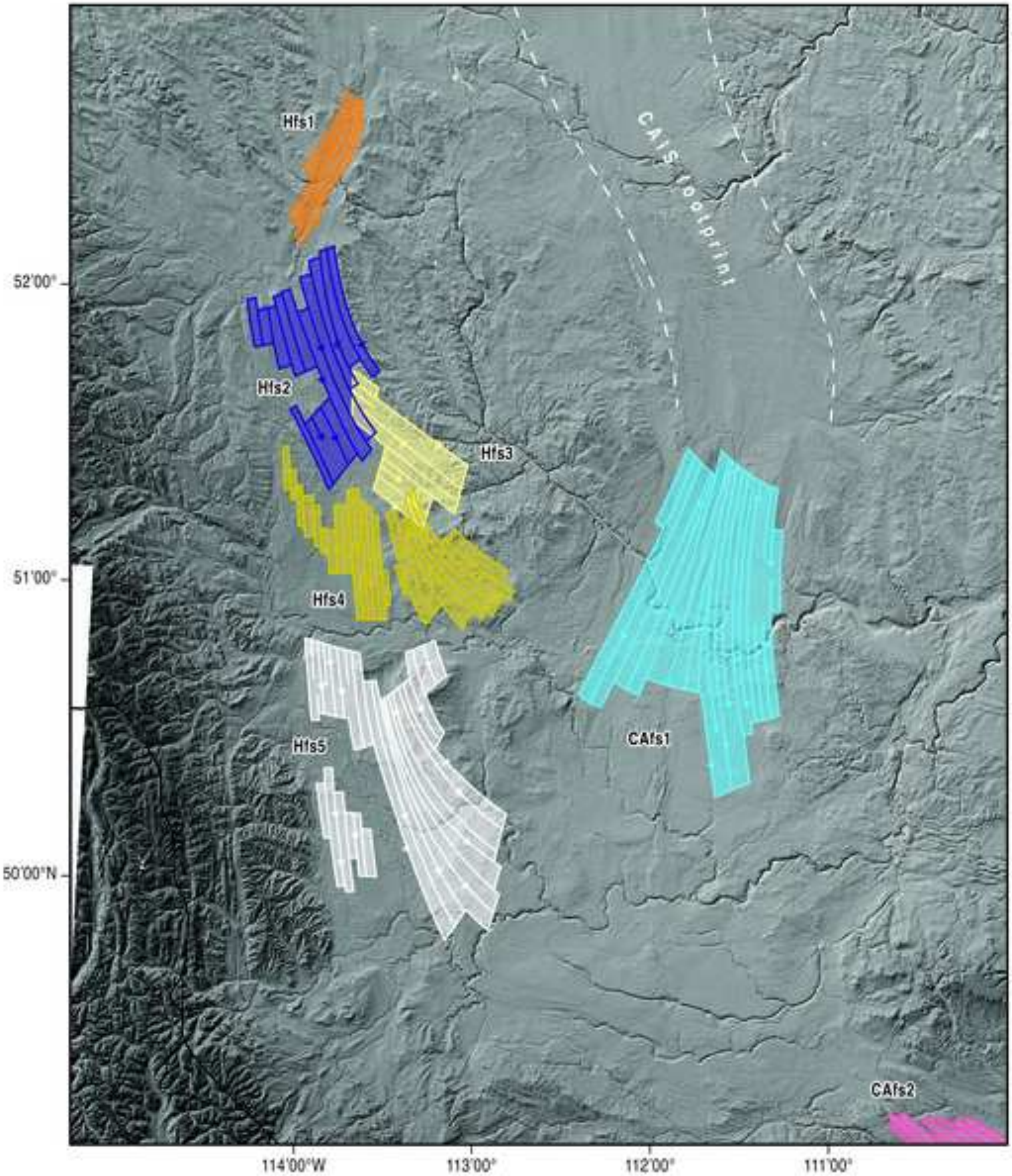

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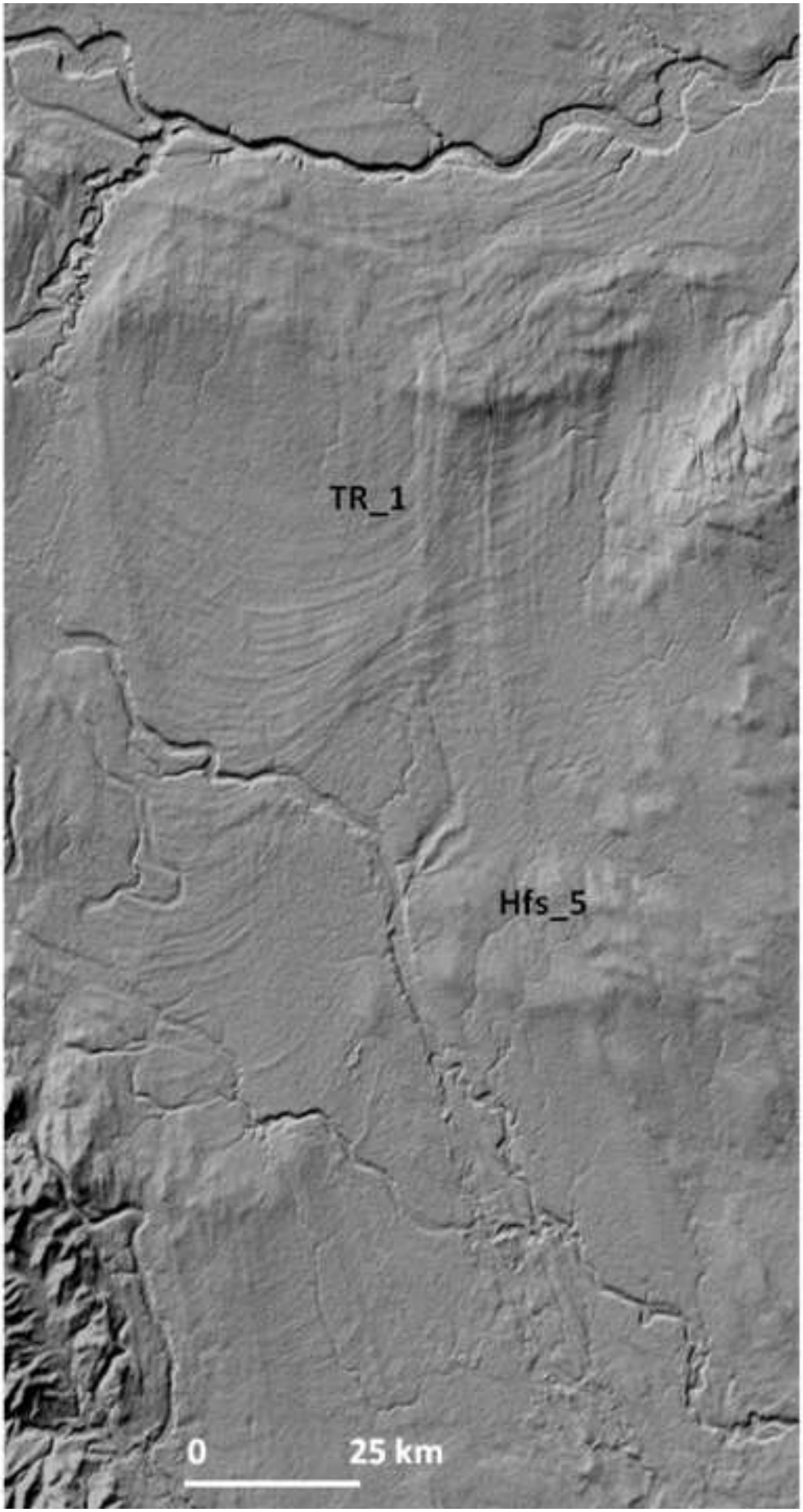

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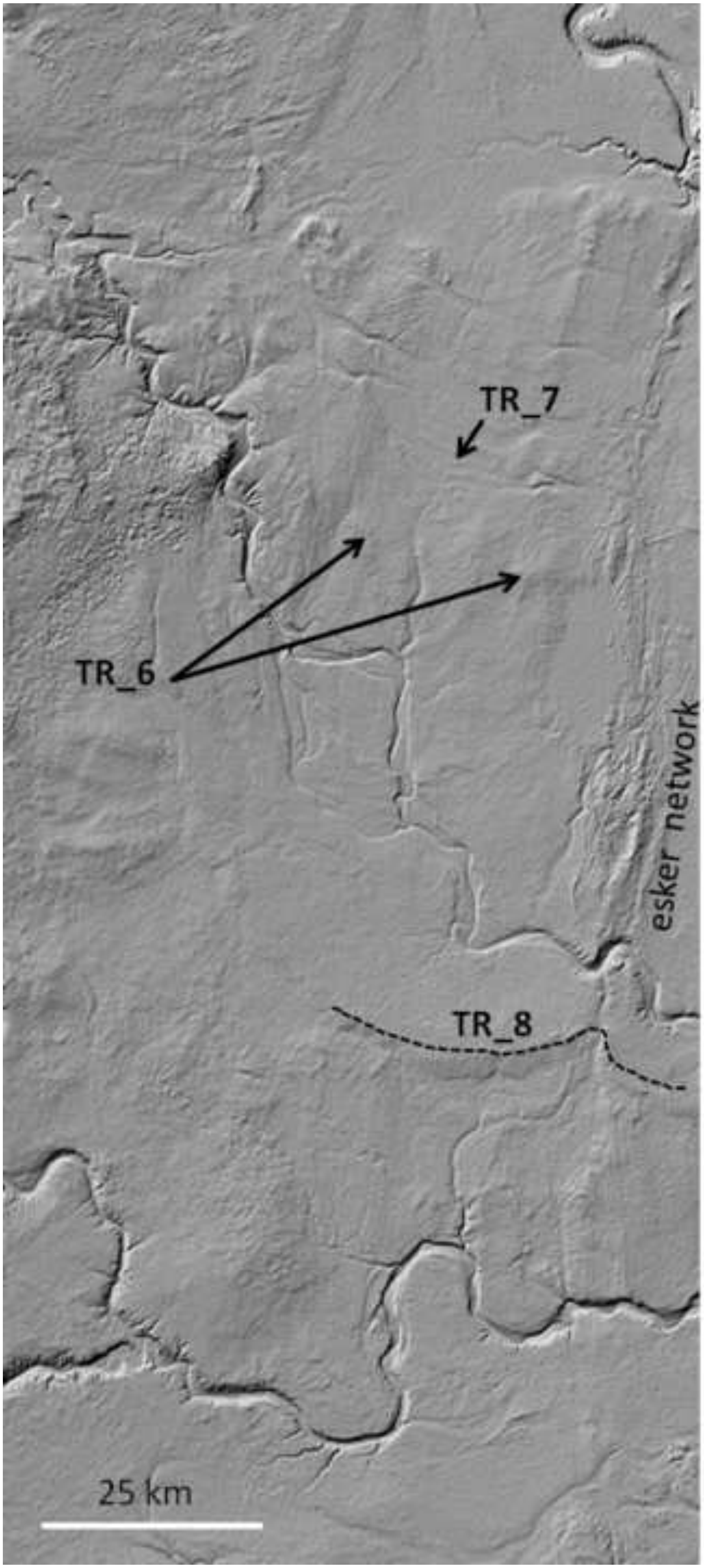

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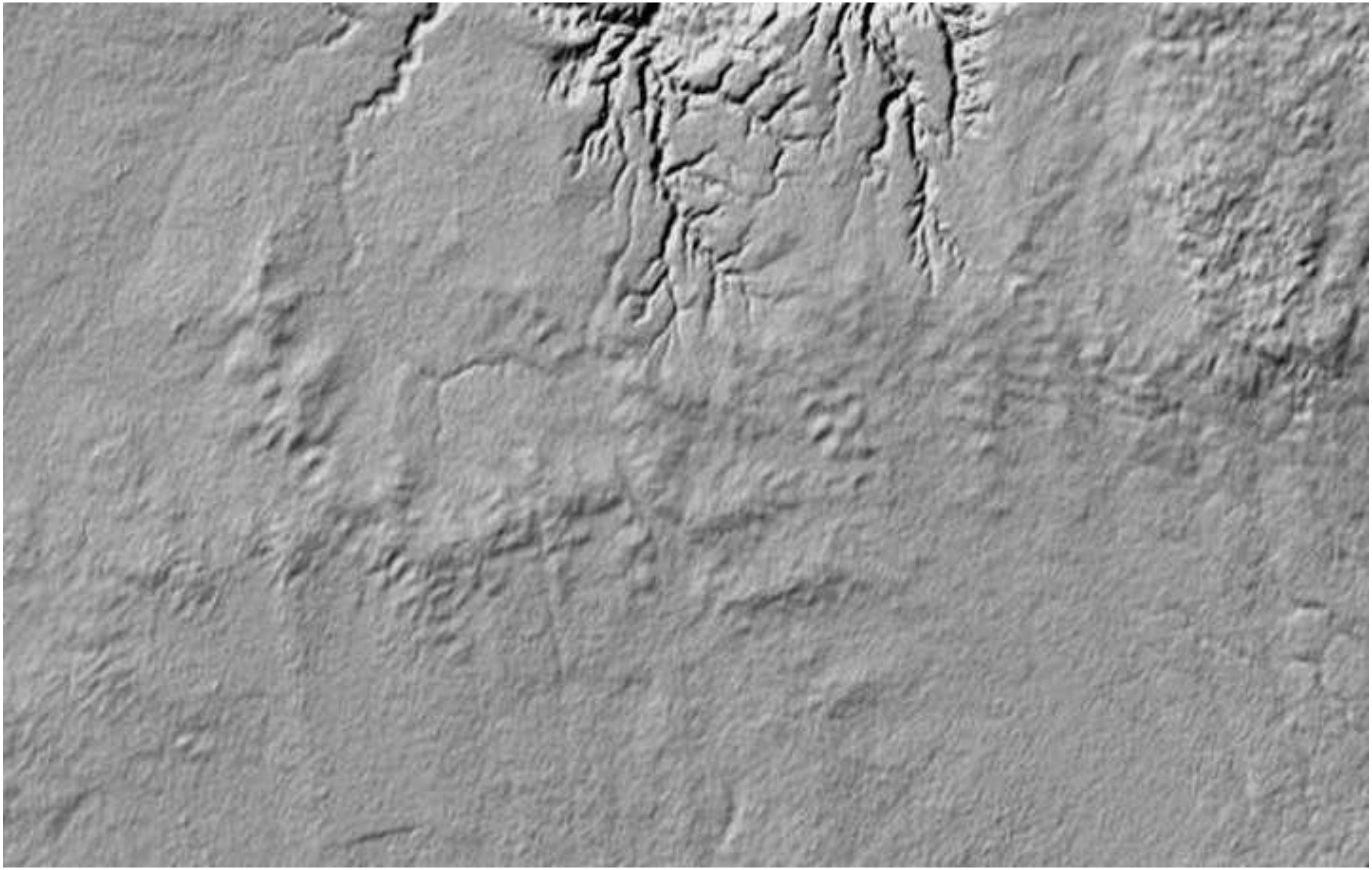

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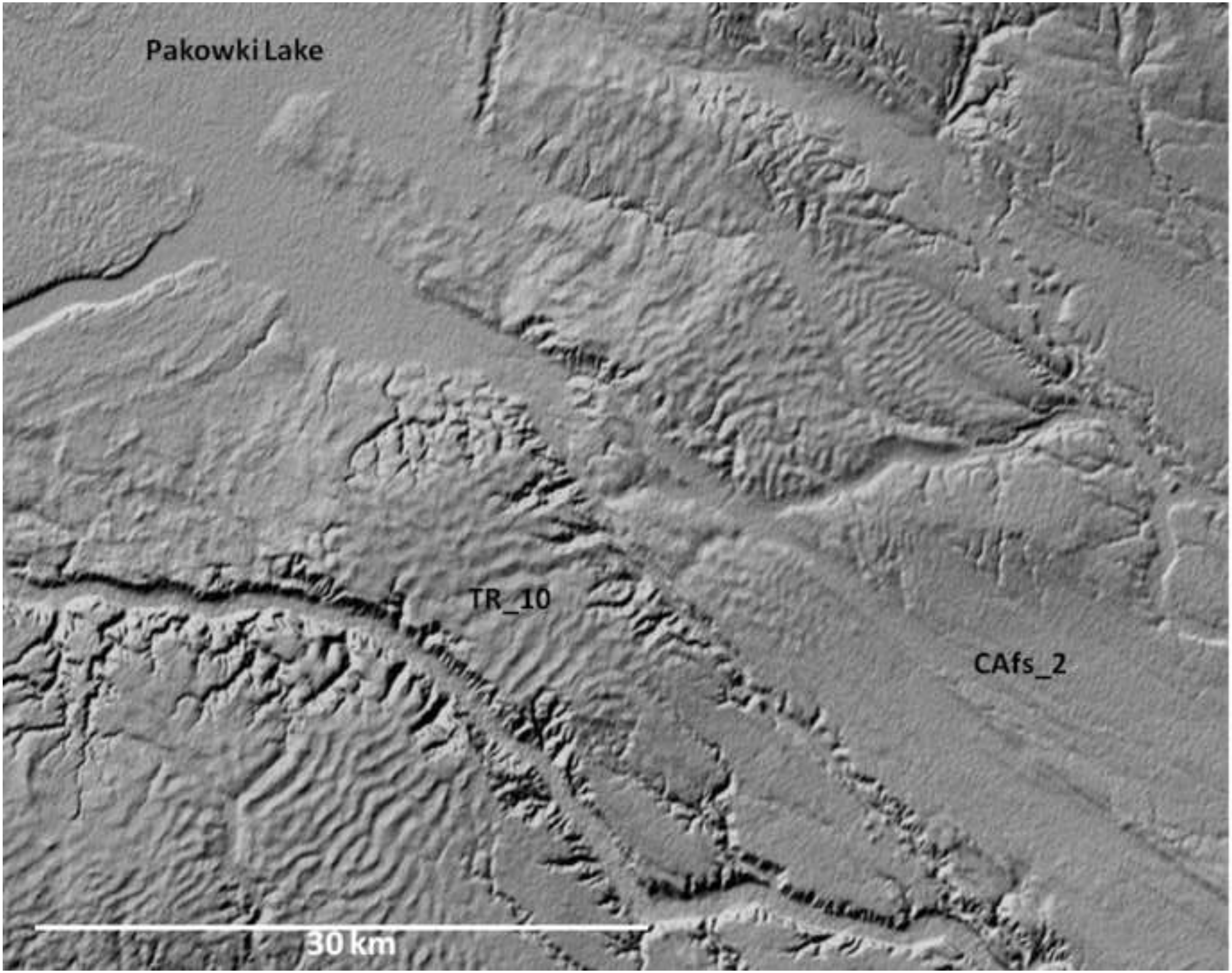

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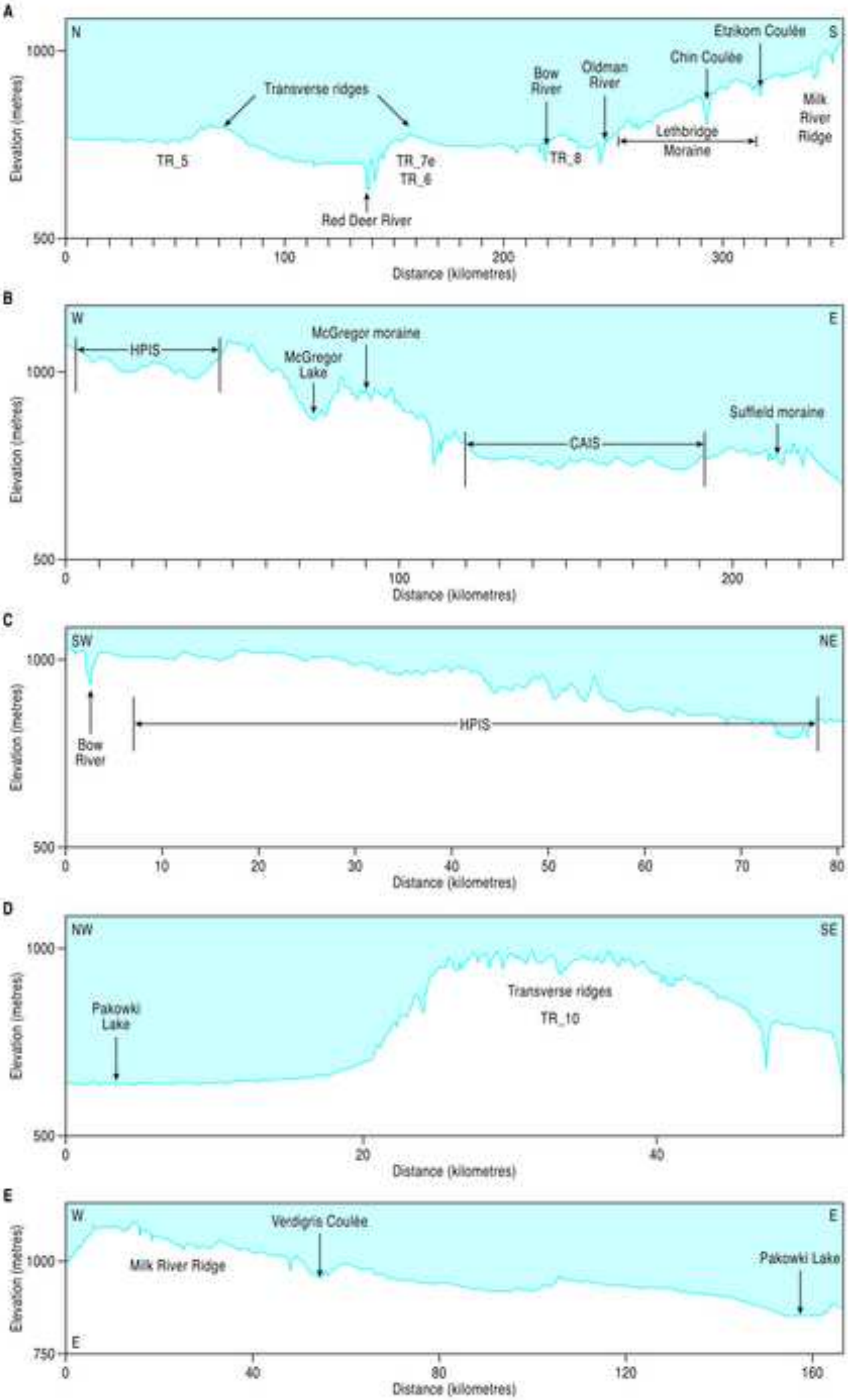

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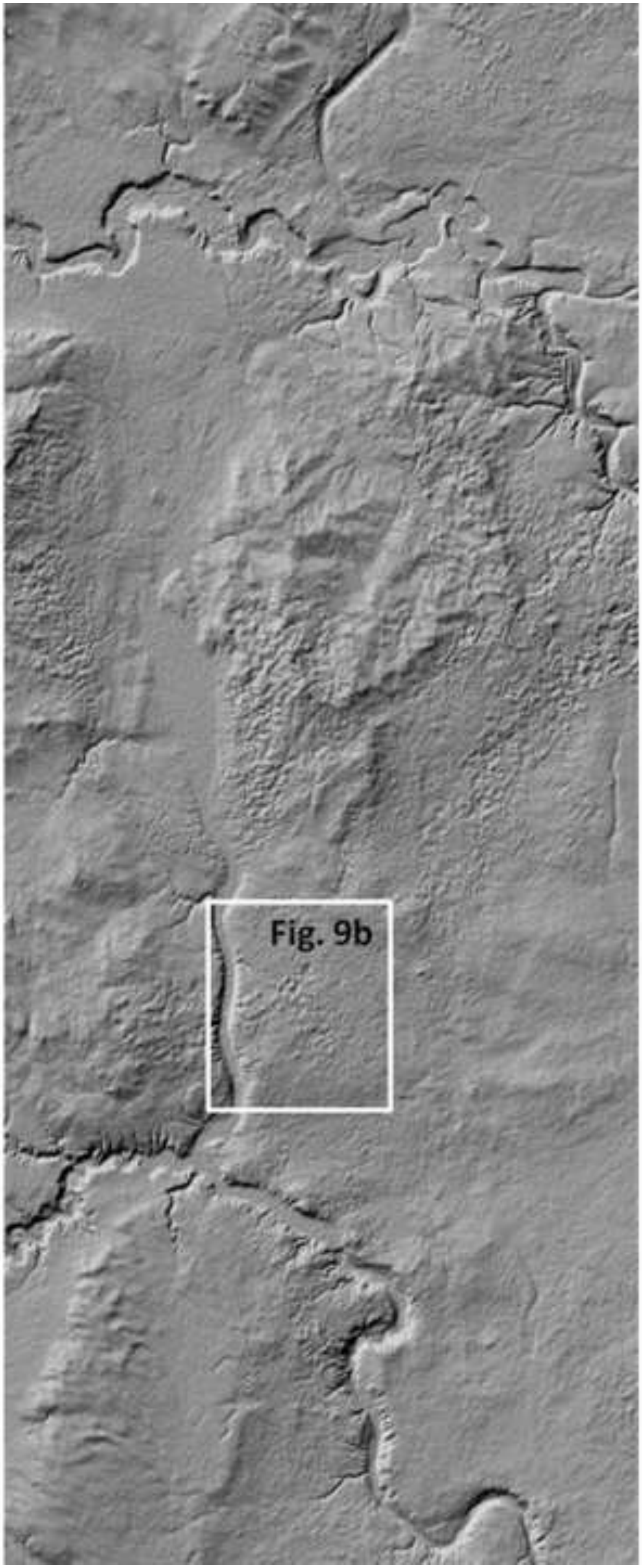

Figure 9b

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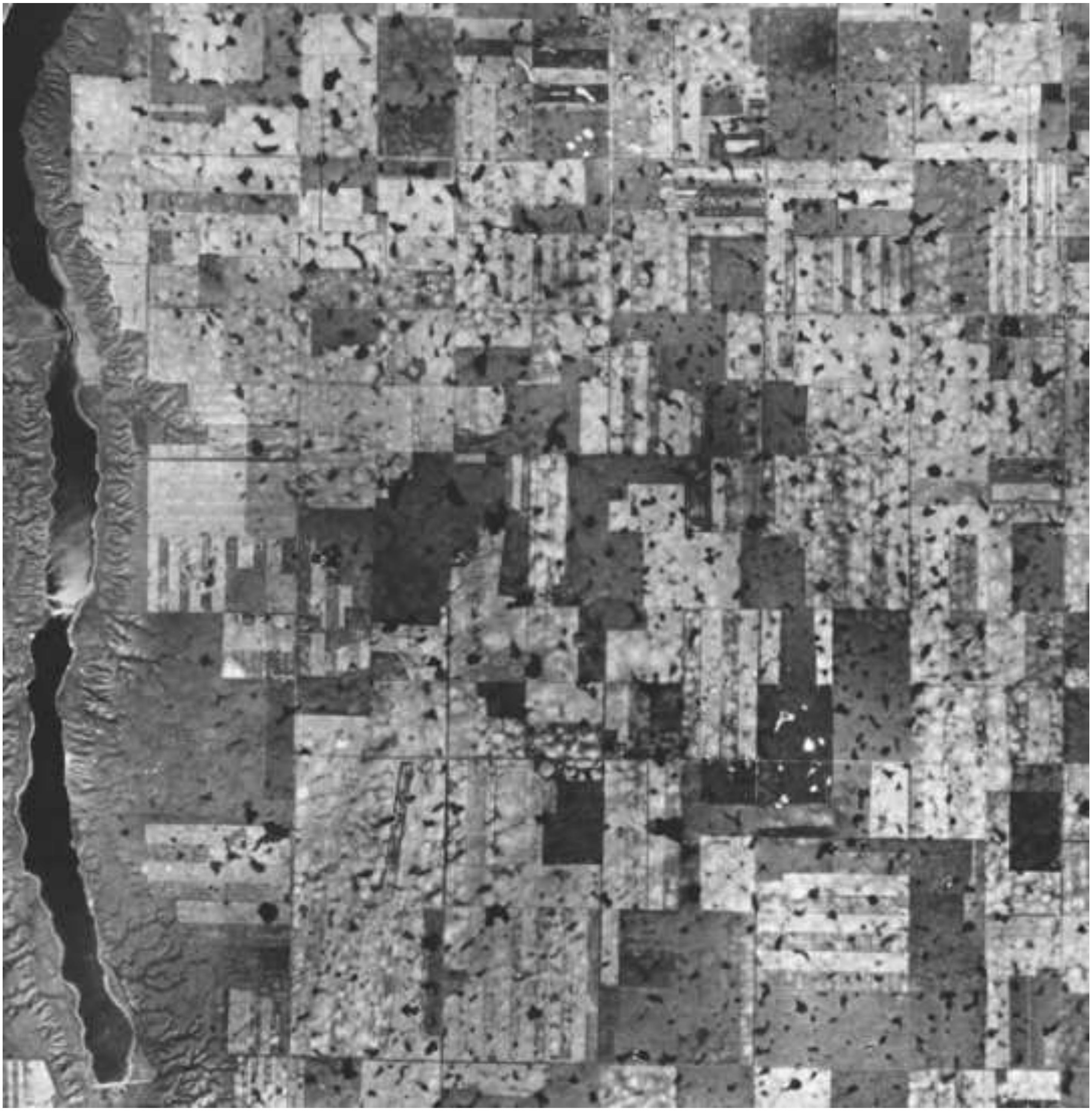

Figure 10
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Figure 11

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Figure 12
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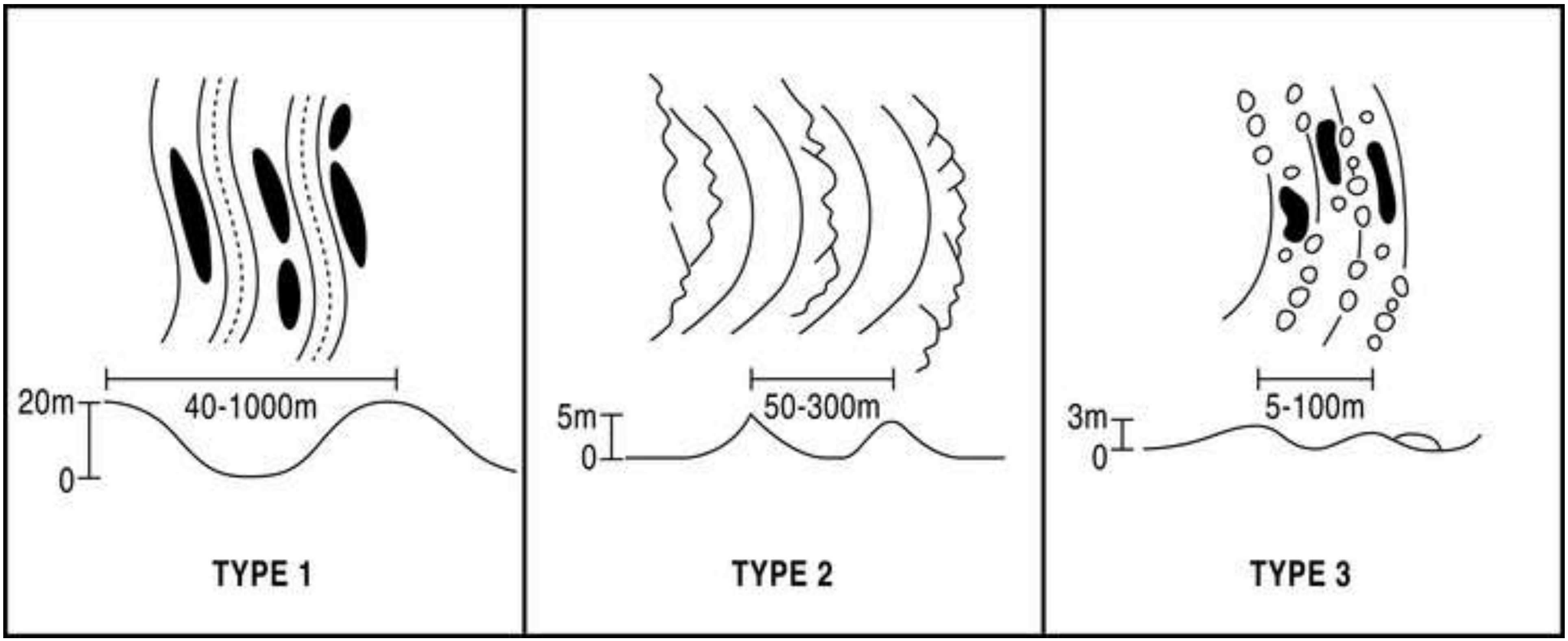

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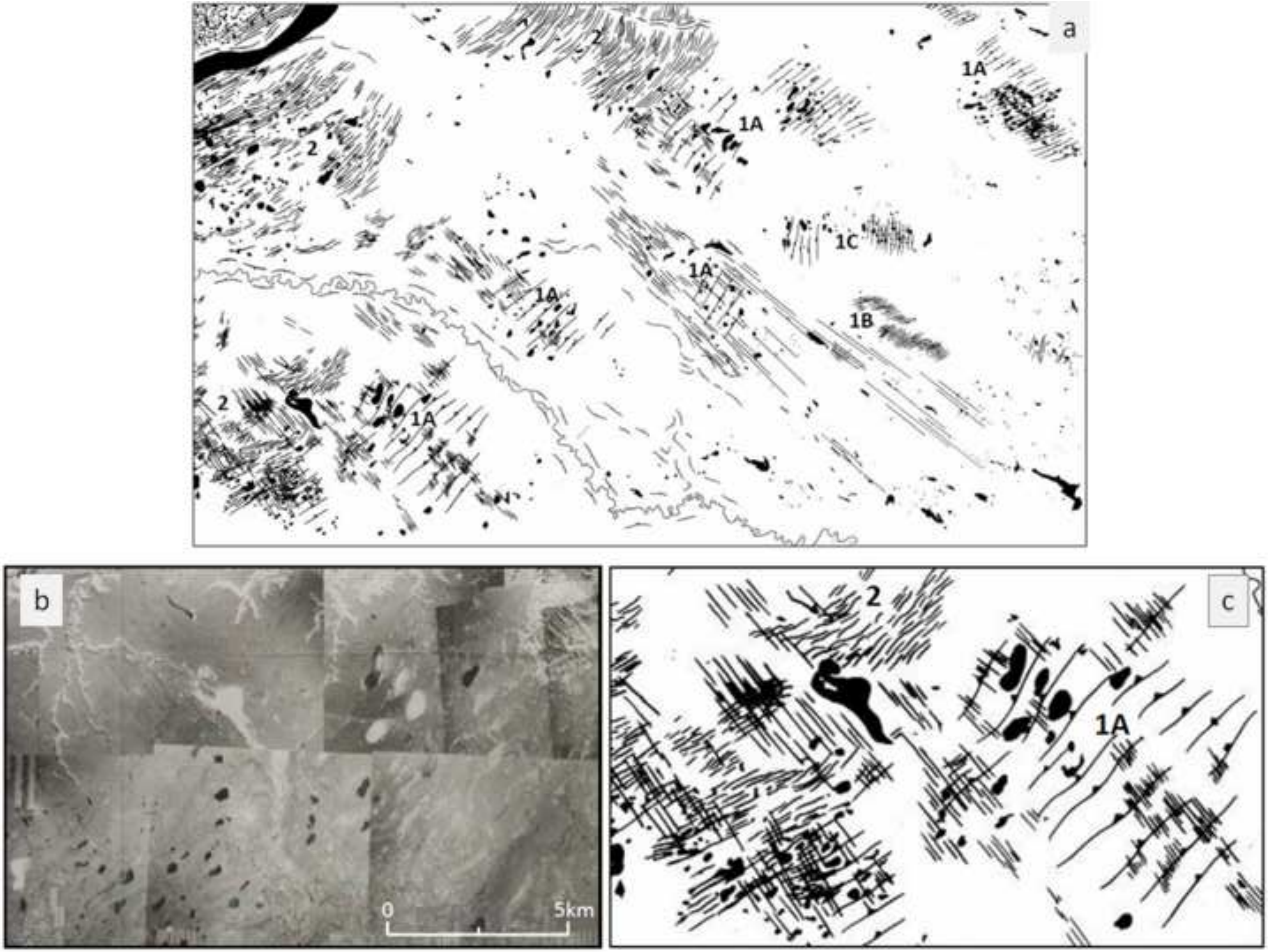

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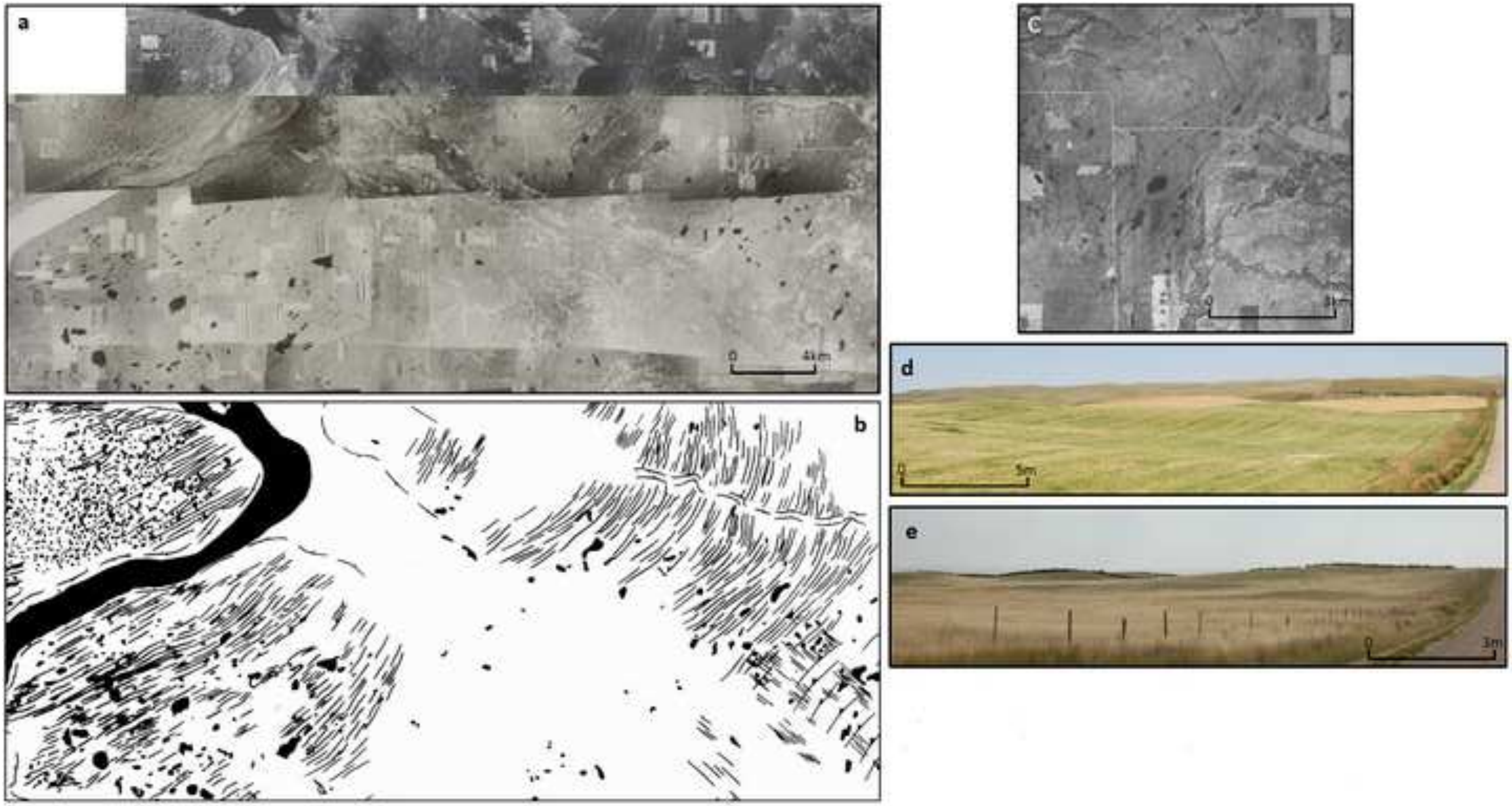

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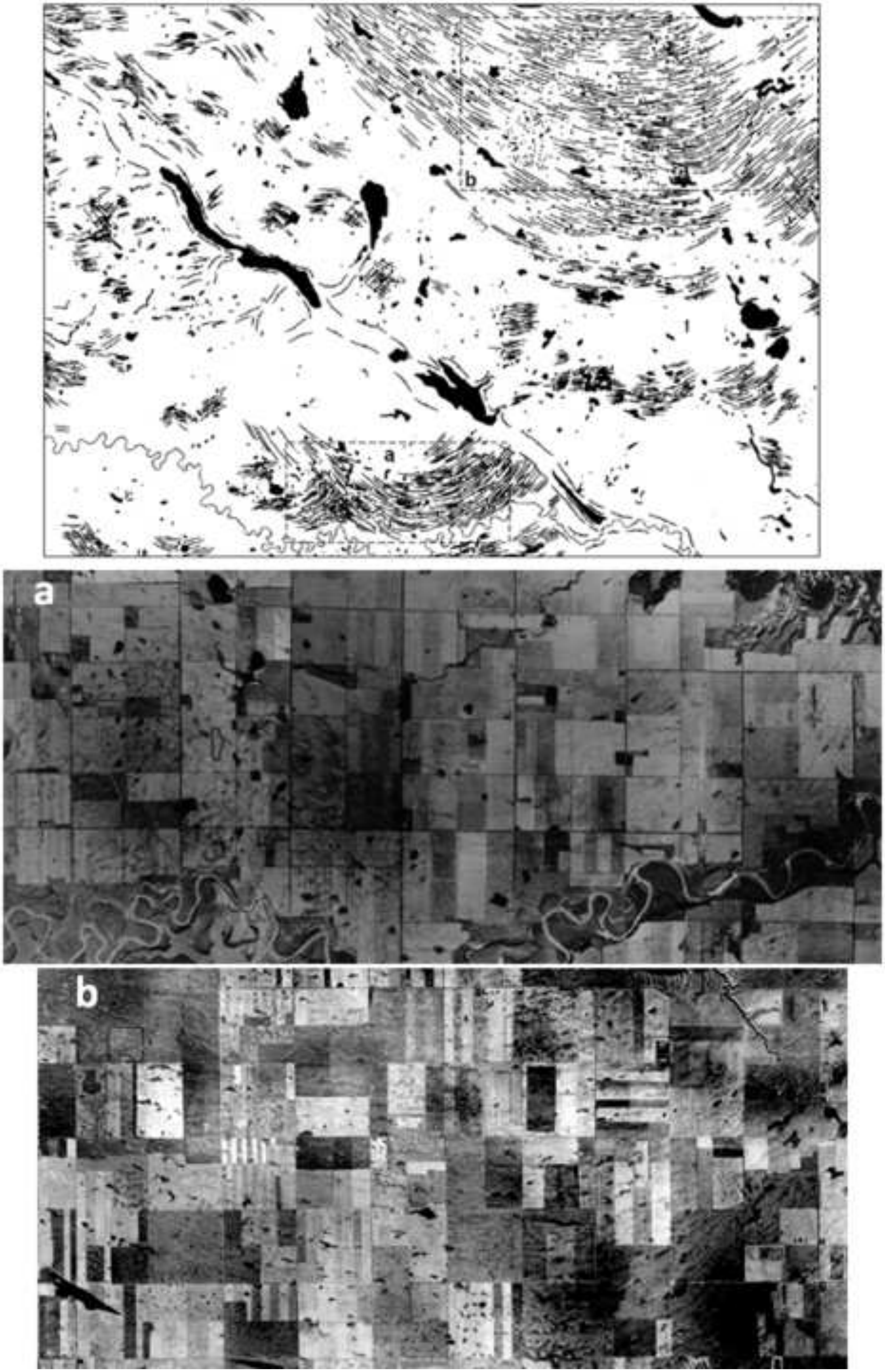

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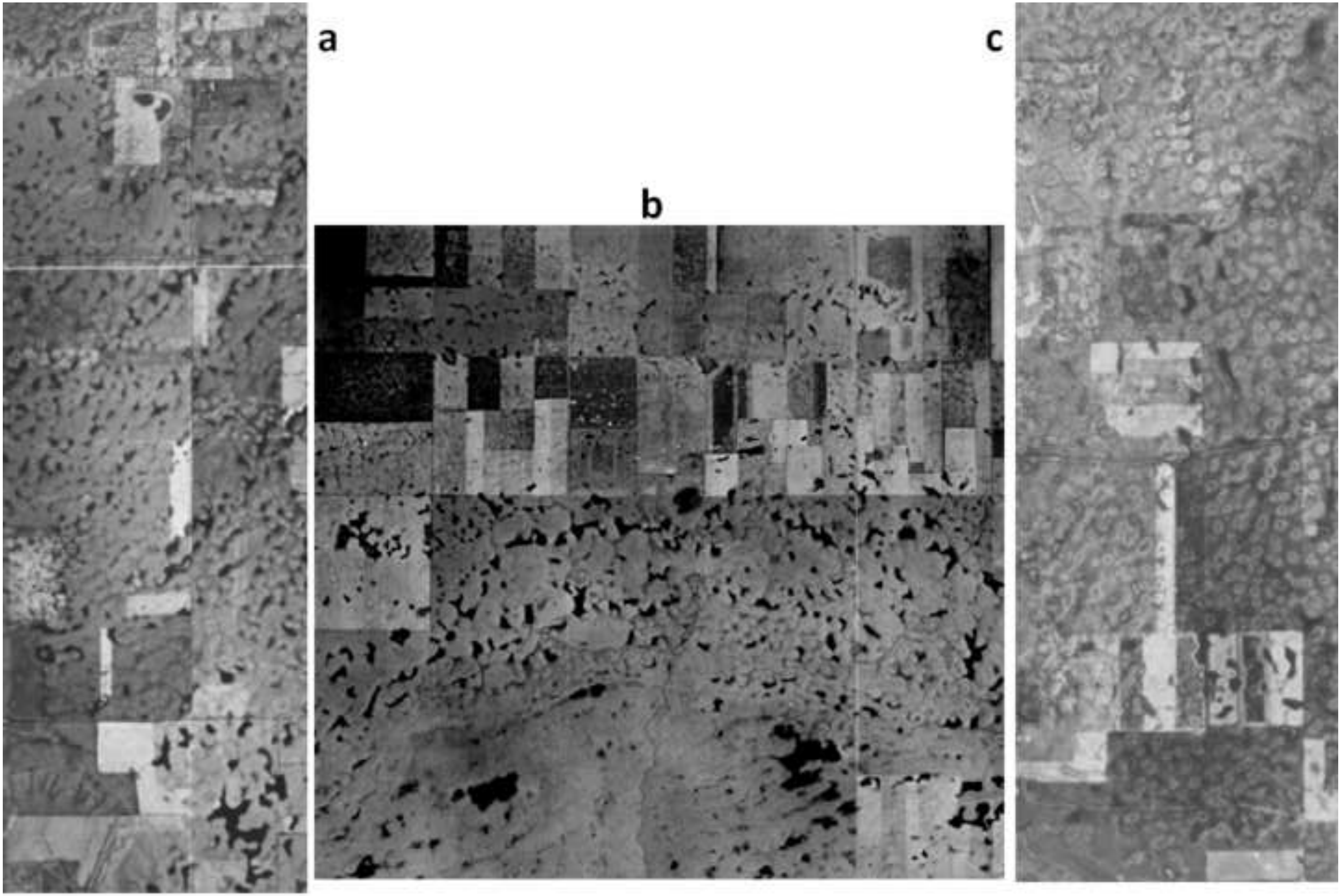

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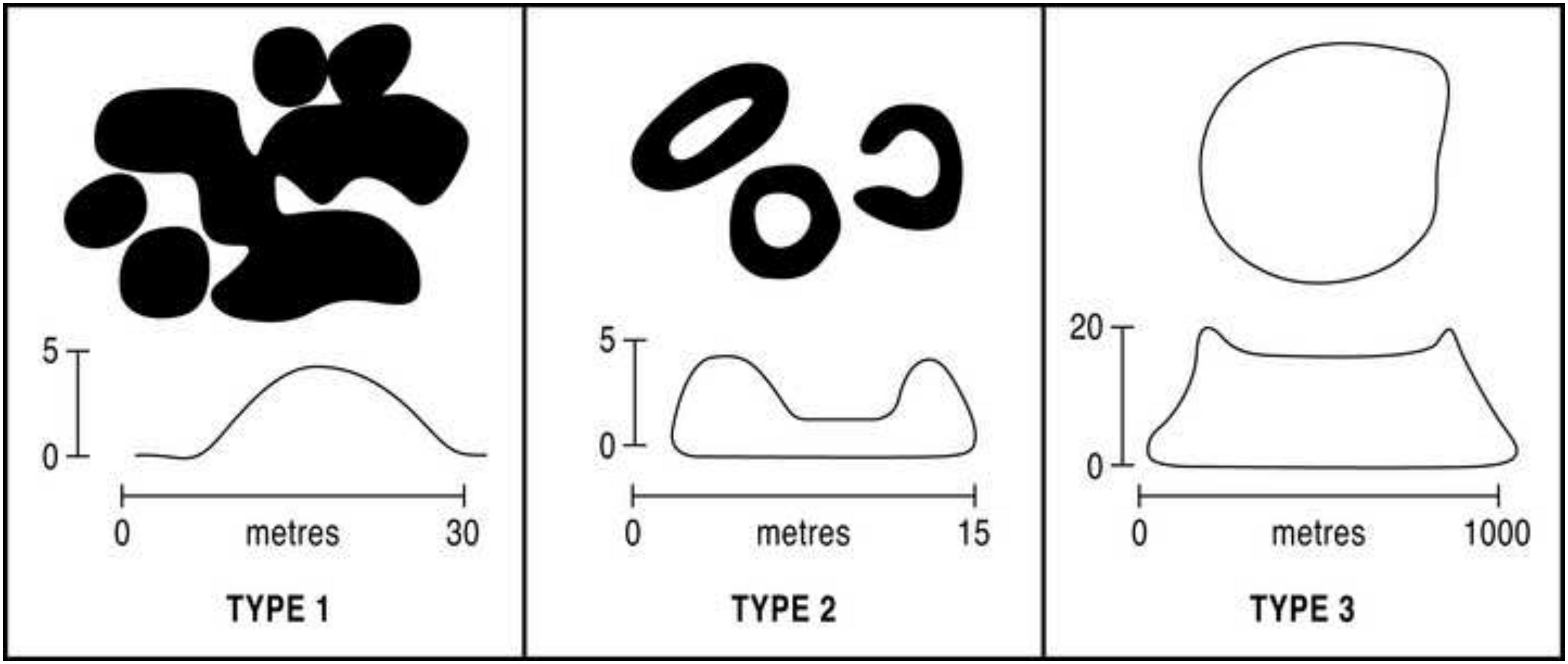

Figure 18
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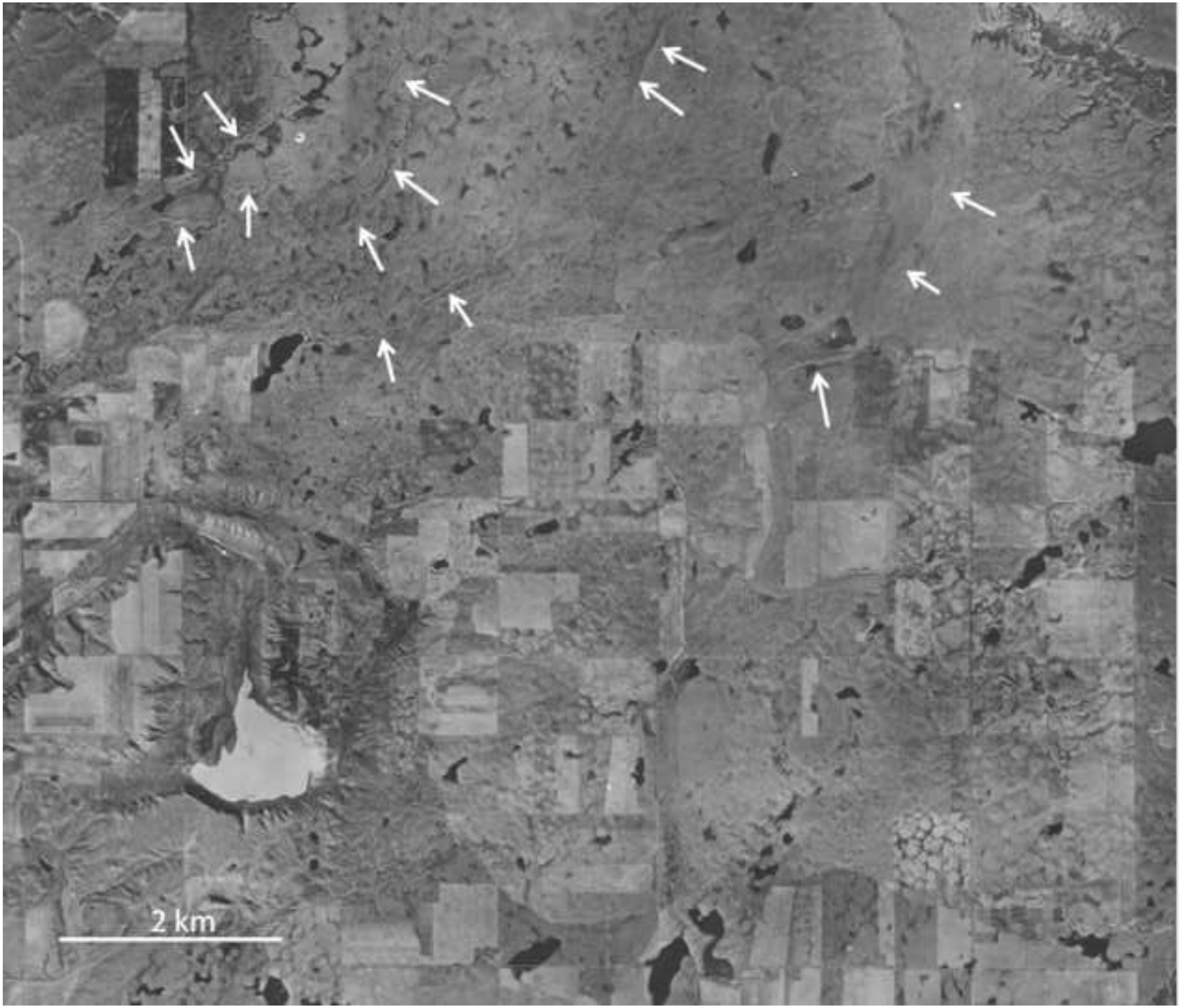

Figure 19

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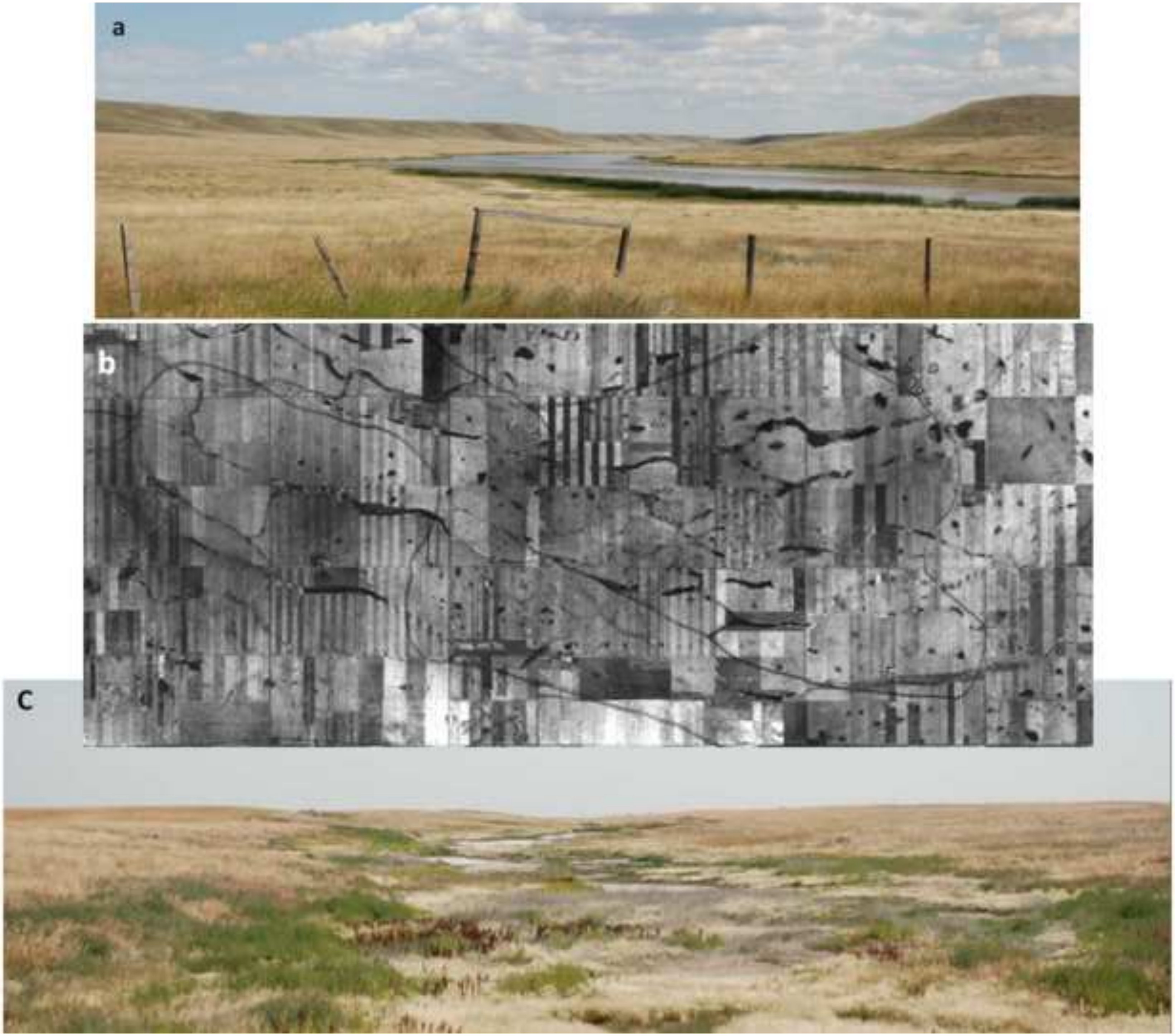

Figure 20

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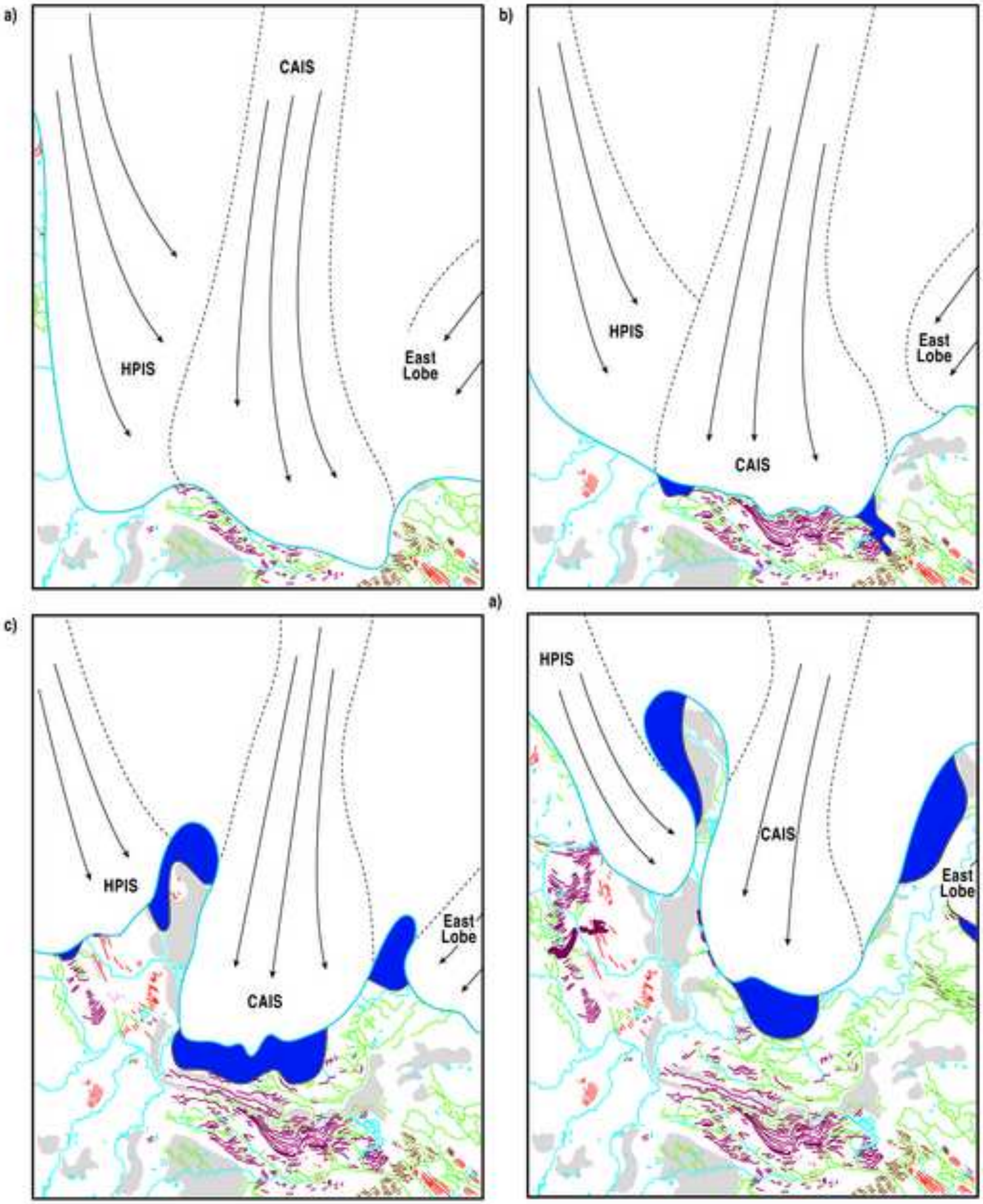

Figure 21a
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Figure 21b
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